Development and Estimation of Traffic Data-Based Operational Measures for Effective Winter Snow Management

A THESIS
SUBMITTED TO THE FACULTY OF
UNIVERSITY OF MINNESOTA
BY

Seong-Ah Hong

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
MASTER OF SCIENCE

Dr. Eil Kwon

August 2014

ACKNOWLEDGEMENTS

I thank God for leading me through all my studies until this moment.

I would like to thank the Minnesota Department of Transportation (MnDOT) for sponsoring this project and providing the data.

I am indebted to a number of people without whom this project would not have been possible. First I appreciate my advisor, Dr. Eil Kwon, for providing me a platform to start the thesis project, for his incredible patience, rigorous challenges, his feedback and pertinent suggestions. I also appreciate the researchers in the NATSRL lab, Soobin Jeon and Dr. Chongmyung Park for their great contributions in developing the computer-based algorithm, and my undergraduate research assistant, Dowon Kim for always being out of his way to help me with.

Last but not least, I am grateful for my friends and family, who encouraged me continuously: My parents and inspiration, Minpyo Hong and Haksil Chang; my spiritual mentors, Isaiah Lee and Loisy Yoon who always supported me with the unfailing prays; my friends, Jinhong Lee, Myunghee Han, Jinju Lee, Sungji Hong and Sunghee Hong whom I love to be with forever in my life.

ABSTRACT

Snow storms degenerate safety and traffic mobility by creating adverse driving conditions including visibility impairments, reducing pavement friction, obstructed road facilities. Improving the effectiveness of the snow management requires an efficient assessment of the operational strategies with the data that can be directly measureable from the field. While there have been various types of operational measures used in the state DOTs in the US, the traffic data-based operational measures that can quantify the effects of snow plowing activities are still lacking. To be sure, the existing approaches developed to date employed the variations of traffic speed or travel time during the snow events and those measures cannot fully reflect the road weather conditions when traffic is congested.

Developing the operational measures that can objectively and accurately reflect the time-variant road weather conditions is essential in improving the effectiveness of the snow management strategies. In this research, an automatic process is developed for estimating the traffic data-based operational measures for winter snow management. Those measures include the Road Condition Recovery Time (RCR), the estimate of the 'bare-lane regain time', which is the major performance measure of the winter snow maintenance operations at the Minnesota Department of Transportation.

The automatic process was then applied to a sample snow section in Twin Cities, MN. The results of the example application showed that the operational measures can reasonably measure the performance of snow plowing operations by reflecting the impacts of the traffic flow resulted by the time-variant road weather conditions.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

1.1. Problem Statement

It is important to accurately quantify and evaluate the performance of winter snow management during snow events. Well-conducted assessment on the current practices can obviate misusing the resources for the process of snow operations, such as: cost in operating the snow plowing trucks, number of people assigned to snow duty, and tons of materials used. Also, it can improve the effectiveness of the operational process to result in the better output, such as: reduction of travel time delay, improvements in traffic-flow level of service, and decrease in crash rates.

Currently, the most of state DOTs including the Minnesota Department of Transportation (MnDOT) use the "Time to bare pavement" for winter snow operations [1]. The "Time to bare pavement" is defined as the duration from the snow event end time to the "bare lane regain time."

MnDOT defines the bare lane regain conditions as having all driving lanes free of snow and ice between the outer edges of the wheel paths and having less than 1 inch of accumulation on the center of the roadway. It is regarded such conditions indicate that drivers become feel safe to drive with a posted speed limit if traffic is not congested.

Practically, however, the "bare lane regain time" for the snow event is determined by the visual inspections of the field crews involved in the snow plowing operations. Such methodology of determining the "bare lane regain time" possibly imposes the issues of objectivity and accuracy to be compliance with the standards of DOT's.

While, it is evident that the road weather conditions affects the traffic flow behaviors during snow events as substantiated by many researchers. However, the efforts to use the traffic data in determining the operational measure such as the “bare lane regain time” has not been a common practice yet.

The research group at the University of Minnesota Duluth has developed an algorithm to estimate the “Speed Recovery Time” to estimate the “bare lane regain time” using the speed variations during snow events [2]. However, it has been noted that only the inspection of speed variations were not sufficient to make a decision pertaining to “the bare lane regain time,” as the speed variations are affected by both snow and traffic congestion. With those limitations, it was called for developing alternative measurements which can represent the current conditions of traffic flow which is reliable to the traffic congestions, such as the process of a relationship between the two parameters of traffic flow.

1.2. Research Objectives

The goal of this research in to develop an automatic process for estimating the alternative traffic data-based operational measures for winter snow management. The automatic process will be applied to the metro freeways in the Twin Cities, Minnesota, with the winter snow event data in 2012-2013.

With this goal, the following objectives are addressed in this thesis research:

1) Identification of phase change points within the traffic flow process including the "road condition recovery time" which can be a surrogate for the "bare lane regain time."

2) Development of traffic data-based operational measures using the phase change points defined in the study.

3) Development of an automatic process for estimating the operational measures for winter snow management and operations.

1.3. Thesis Organization

The remaining chapters of this thesis were organized as follows:

Chapter 2 presents a relevant literature review on the following subjects: 1) Existing research efforts on the operational measures for winter snow management, and 2) Effects of the weather conditions on the traffic flow behaviors.

Chapter 3 describes the dataset used in this study. The data collection process and the summary of the collected will be provided.

Chapter 4 presents the analysis of the snow-affected traffic flow process using the section-wide speed variations and the Section-wide Fundamental Diagrams (SFD). Based on the result of analysis, a set of phase change points was identified in the traffic flow variations.

Chapter 5 describes the automatic process for estimating the operational measures for winter snow management. First, a set of the alternative operational measures based on traffic data will be developed using the phase change points identified in the previous chapter. Then, the step-by-step process of the algorithm developed in this study will be presented.

Chapter 6 demonstrates the applications of the automatic process to the sample snow section. The results of estimation of the alternative operational measures for the given snow event cases will be provided and interpreted.

Chapter 7 summarizes the research efforts, key findings, conclusions, and recommendations for future research.

CHAPTER 2: LITERATURE REVIEW

In Chapter 2, the relevant literatures and the up-do-date practices of operational measures for winter snow management will be reviewed. The following subjects will be covered:

2.1 Existing Operational Measures for Winter Snow Management based on Traffic Data

2.2 Existing Studies on Traffic Flow Behaviors under the Inclement Weather Conditions

2.1. Existing Operational Measures for Winter Snow Management based on Traffic Data

Iowa Department of Transportation

Iowa Department of Transportation estimates the acceptable speed reduction during a storm as in

Equation 1 [3]:

$$\text{Acceptable Speed Reduction} = \text{BVSR} \times \text{SSI}$$

Equation 1

In Equation 1, BVSR (Base Value of Speed Reduction) indicates the maximum acceptable speed reduction for a given route under the worst storm. SSI (Storm Severity

Index) refers the severity level of a storm which is determined by the different elements of the snow storm, such as the storm type, storm temperature, wind conditions and its behavior characteristics. Table 1 provides the values of BVSR (Base Value of Speed Reduction) for different route categories in terms of their priorities. Also, the table summarizes the set of index values which will be used in determining the SSI for a certain conditions of a snow storm. The formula to calculate SSI is provided in Equation 2:

$$SSI = \left[\frac{1}{b} \times \left[ST \times T_i \times W_i + B_i + T_p + W_p - a\right]\right]^{0.5}$$

$$\text{where } a = 0.0005 \text{ and } b = 1.6995$$

Equation 2

The success of the performance of winter snow management will be determined by comparing the measured speed drop to the "Acceptable Speed Reduction" resulted by the above process.

Table 1: Base Value of Speed Reduction and SSI formula [3]

Base Value of Speed Reduction (mph)	Priority A	Priority B	Priority C	
	17	22	24	
Storm Type (ST)	Freezing Rain	Light Snow	Medium Snow	Heavy Snow
	0.72	0.35	0.52	1
Storm Temperature (T_i)	Warm	Medium Range	Cold	
	0.25	0.4	1	
Wind Conditions in Storm (W_i)	Light	Strong		
	1	1.2		
Early Storm Behavior (B_i)	Starts as Snow	Starts as Rain		
	0	0.1		
Post Storm Temperature (T_p)	Same	Warming	Cooling	
	0	-0.087	0.15	
Post Storm Wind Conditions (W_p)	Light	Strong		
	0	0.25		

University of Wisconsin at Madison [4]

In an attempt to develop the traffic data-based operational measure for quantifying the performance of winter snow management, the regression model to estimate the "speed recovery duration" was formulated as a function of several variables including the maximum speed reduction (%), time to maximum speed reduction, and snow depth due to a given snow storm, as in Equation 4, using the traffic data collected from the Madison, Wisconsin:

$$\text{Speed Recovery Duration} = 9.68 + 9.926\times\text{MSRPCENT} - 0.086\times\text{StoS2MSR} + 0.493\times\text{Crewdelayed} - 0.222\times\text{Snowdepth}$$

Equation 3

where,
MSR = Maximum speed reduction,
StoS2SD = Time lag to speed drop after snow storm starts
StoS2MSR = Time to MSR after snow storm starts
Crewdelayed = Time lag to deploy maintenance crew after snow storm starts
Snowdepth = Snow precipitation

While their effort needs to be recognized as one of the first ones in applying traffic-flow data for quantifying the performance of snow operations, Kwon [2] pointed out that the method of piecewise linear regression resulted in the questionable models, e.g., negative parameter of the "Snowdepth" variable.

Michigan Department of Transportation [5]

Michigan Department of Transportation adopted the traffic data –based performance measure called "Weather Travel Impacts." The measure determines the success of the snow operational measures by the fact whether the normal speeds were regained within two hours or less, 80% of the time for winter weather events. To develop the normal speeds to be used as a reference, MDOT collected the speed data along I-96, from Ionia County to the Oakland County line during the winters of 2009-2012. The portable trailers with microwave sensors were attached to detect speed before, during and after a winter storm event. Also, storm start and end times are recorded by maintenance staff along with other information about the intensity and temperatures during the storm.

Even though such effort to use the traffic data in estimating the performance of the winter snow operations has to be recognized, only employing the speed variations in determining the road recovery time has a limitation in the case of traffic congestion.

2.2. Traffic Flow Behaviors under the Inclement Weather Conditions

2.2.1. Impacts of Weather Events on Traffic System

Weather events including rain, snow and fog build up inclement driving conditions which are different from dry normal condition. The inclement conditions describe visibility impairments, reducing pavement friction, obstructed road facilities, restricted vehicle performance, etc. Depending on weather type, duration, and intensity, the scenarios of roadway condition may vary and that impacts on transportation system also differ.

Typically, the influences of the inclement weather on the transportation system can be examined in three parts: safety, traffic flow, and operational productivity.

Safety

The environment with lowered visibility and slippery pavement can result in the increase in frequencies and severities of crashes. According to the crash data collected in the US in 1995-2008, the weather-related crashes were reported greater than 1.5 million vehicle crashes per year while comprising 24% of the whole population of crash incidents each year [6]. Among the weather-related accidents, the significant majority of crashes happened on wet pavement and during rainfall, reporting 75% and 45% of the entire weather-related crashes respectively. While, small amount of crashes occurred during winter snow conditions; amount of crashes in snow or sleet condition involved 15% and those on icy pavements accounted for 13% of weather-related incidents [6]. This result reflects the tendency of drivers who became more cautious during snow event than rainfall. While, the study efforts to identify the impacts of weather events on the severity of crash were also conducted. It was observed that 17% of the entire crash fatalities was attributed to the weather events, which implies that the weather condition also aggravate severity of crashes as well as the increase in the number of amount [6]. A similar study was conducted in Canada [7]. They disclosed that snow days had fewer fatal crashes than dry days, but more nonfatal-injury crashes and property-damage-only crashes were reported [7]. The study also showed that the first snow day of the year was substantially more dangerous than other snow days in terms of fatalities, particularly for elderly drivers [7]. Some comparable observations with the previous study relating to the behavior of motorists under snow events were also observed in the study in the US [8].

Traffic Flow and Mobility

The nation-wide efforts to measure and quantify the influences of inclement weather on traffic flow have been conducted using the empirical or simulated data. Ibrahim et al. [9] identified the impact of inclement weather on traffic speed by differentiating the types (rain and snow) and intensity (light and heavy) of precipitation. It was observed the minimal reductions in the operating speeds in light rain, but significant reductions in heavy rain: in light rain, a 2.0 km/h (1.7%) reduction in speed during free-flow conditions was found typical; in heavy rain, a 5.0-10.0 km/h (4.4-8.7%) reduction in free-flow speed was estimated [9]. Likewise, light snow was found to have minimal effects on speed but heavy snow imposes potentially large effects on operating speeds. Light snow resulted in a statistically significant drop of 0.96 km/h in free-flow speeds. Heavy snow resulted in a 38.0 - 50.0 km/h free-flow speed reduction (33- 43%) [9]. More recent study by Rakha et al. provides consistent findings for major traffic flow parameters: the light rain (0.01 cm/h) results in reductions in the traffic stream free flow speed, speed at capacity, and capacity in the range of 2-3.6%, 8-10%, and 10-11%, respectively [10]. Also, light snow (0.01cm/h) produces reductions in free flow speed, speed at capacity, and capacity in the range of 5-16%, 5-16%, and 12-20%, respectively [10]. They concluded that the reductions in the free flow speed and the speed at capacity both increased under the greater intensity of rain or snow. While, traffic jam density and roadway capacity reduction remain constant for all weather intensities at a specific site [10].

Operational Productivity of Traffic System

The inclement weather conditions also deteriorate operational productivity of transportation system while increasing the cost of operating and maintenance of winter road maintenance, traffic management, emergency management, and law enforcement. According to FHWA data collected in 1997-2005, winter road maintenance accounted for roughly 20% of state DOT maintenance budgets and that state and local agencies spend more than 2.3 billion dollars on snow and ice control operations annually [11]. In addition, trucking companies and commercial vehicle operators lose an estimated 32.6 billion vehicle hours due to weather-related congestion in 281 of the nation's metropolitan areas each year [12]. Nearly 12% of total estimated truck delay is due to weather events in the 20 cities with the greatest volume of truck traffic [12]. The estimated cost of weather-related delay to truck companies ranges from 2.2 - 3.5 billion dollars annually [12].

All these studies show that inclement weather may have a significant and comprehensive impact on the transportation system, which cannot be ignored by planners and decision makers.

2.2.2. Traffic Flow Behaviors under the Inclement Weather Conditions

To effectively mitigate the adverse impacts of the inclement weather on traffic system, FHWA has involved researchers and universities in the US and abroad to tackle an organized research framework upon Weather Responsive Traffic Management (WRTM) [13]. The WRTM research projects include: collecting and analyzing data, developing models and tools to improve the analysis, and modeling/prediction of traffic flow in all types of weather conditions. In a project completed in 2008 by Rakha et al., the impacts of inclement weather on traffic were quantified by developing Weather Adjustment Factors (WAF) for key traffic flow parameters (e.g., the free flow speed, speed at capacity, capacity, and jam density) [10]. The WAF for each traffic parameter was estimated by developing multiple linear regression model using precipitation type, precipitation intensity, and visibility level as independent variables. This study made a contribution to form fundamental basis for developing WRTM strategies. For example, the WAF can be implemented in the HCM freeway procedures by multiplying the base clear-condition factors by the WAFs. The potential applications of WAFs on the WRTM strategies include: (1) the capacity values that are used for the design of roadways could be modified to reflect the impact the impact of precipitation. (2) the procedures could be incorporated in real time advanced traffic management system applications, namely, ramp metering or adaptive signal control algorithms. This refinements in traffic control devices provides better estimates of roadway capacity and thus enhance these real-time systems [10]. In addition, researchers already incorporated such results in analyses using traffic simulation modeling tools, such as DYNASMART, DynaMIT, AIMSUN, CORSIM, INTEGRATION, PARAMICS, VISSIM and others [13].

Moving from macro to micro analysis, FHWA looked at individual driver responses to weather conditions, such maneuvers as: changing lanes, merging onto a freeway, making a left turn across traffic at an intersection, and adjusting the distance behind a lead vehicle. Using video data from intersections in Virginia and test tracks in Japan, the manner by which drivers perceive and accept gaps in traffic streams were analyzed and used to develop relationships that can support traffic signal phasing adjustments during weather events [14]. Notwithstanding the progress in the study on the microscopic traffic flow behavior during weather conditions, this area remains to have limitations and erroneous future work is expected to illuminate the process of data collection and integration and theoretical analysis of driver behavior in adverse weather. In addition, modeling of headway distribution that considers vehicle class, vehicle type, time of the day, and day of the week could benefit a process of determining traffic stability.

The goal of the above studies within the WRTM framework is to inform model development and decision-support tools to allow a user to translate current and forecast conditions to traffic impacts. In addition to the macroscopic and microscopic traffic flow research, the FHWA RWMP modified two Traffic Estimation and Prediction System (TrEPS) tools to account for weather impacts and improve their traffic estimation and prediction capabilities and overall utility [15]. Those models of TrEPS are DYNASMART-

P, a system for transportation planning, and DYNASMART-X, a real-time system for predicting traffic conditions and patterns [13].

Based on the literature reviews on the weather impact on the traffic flow, one of the main issues with the existing approaches was that most of the studies assumed that the amount of impacts on traffic flow sustained equal within a weather event. In reality, however, the road weather conditions show a wide ranges of variations through a single weather event, causing the traffic flow responds in a different ways to the dynamically changing environments. This issue has prevented the results from being used in any practical purposes, such as the development of the traffic data-based operational measures of winter snow operations. To resolve this issue, it is needed to study the temporal process of traffic flow with the connection of the varying road weather conditions during snow events.

CHAPTER 3: COLLECTION OF TRAFFIC AND ROAD WEATHER DATA

In Chapter 3, the study area and dataset used for the research will be described using the following terms:

3.1. Configuration of Snow Sections

3.2. Data Collection Process and Collected Data

The study area is comprised of selected "snow sections" which will be identified and defined in Chapter 3.1. The dataset for the study includes three types: road maintenance data, road weather data and traffic flow data. The procedure for processing each type of data will be explained further in Chapter 3.2.

3.1. Configuration of Snow Sections

The overall scheme of winter snow management and operations are planned, executed and evaluated within the framework of the snow route system. Currently, the snow route system is made up of the primary freeways in the vicinity of the metropolitan network in Twin Cities, Minnesota. Figure 1 includes a map of the snow route system which was provided by the Office of Maintenance Operations of the Minnesota Department of Transportation (MnDOT). The snow route system consists of 75 snow routes and each individual snow route is identified by the different colored threads on the map. Under the MnDOT's policy, snow routes in close proximity were grouped to be assigned to a truck station for the control of snow management and operations for the given snow routes. It should be noted that the snow route system in the metropolitan area is associated with 18 truck stations across the region. (http://www.dot.state.mn.us/maintenance/pdf/research/manual/Ch1.pdf)

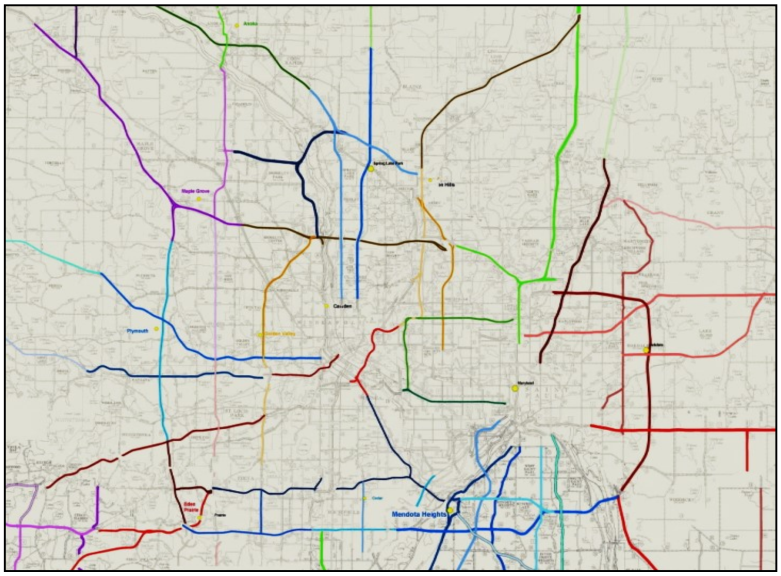

Figure 1: Snow Route System in Twin Cities, MN, USA

According to the practices of the MnDOT, snow plowing operations and performance evaluations are independently conducted for each individual snow route. The bare lane regain time, the main performance measure used by the MnDOT, is reported based on the snow route system, which means that one snow route is assigned with one specific bare lane regain time.

However, one separate snow route consists of multiple segments of different highways. Figure 2 (A) shows the two selected snow routes which are located in the central area of the Twin Cities. The identification numbers of the snow routes include TP9F0251 and TP9F0253 under the MnDOT Snow Route Identification System. As shown in the figure, Snow Route TP9F0251 is comprised of two segments of different freeways (i.e., I-35E and TH.694) and thus Snow Route TP9F0253 (i.e., I-94 and TH.52) is done in a similar fashion.

In this study, such types of snow routes were divided into two different components called “snow sections” which are made up of a consistent freeway. For example, as appears in Figure 2 (B), Snow Route TP9F0251 was divided into two snow sections which include the freeway segment of I-35E and TH.694, respectively. In a similar fashion, Snow Route TP9F0253 was divided into two snow sections that include freeway segments I-94 and TH.52, respectively. It should also be noted that the boundaries of snow sections were designed in a way that the traffic flow can maintain consistent characteristics across the snow section without significant interruptions incurred by the traffic flow entering and exiting through the ramps connected to the various freeways. In this study, the four snow sections shown in Figure 2 (B) will be utilized.

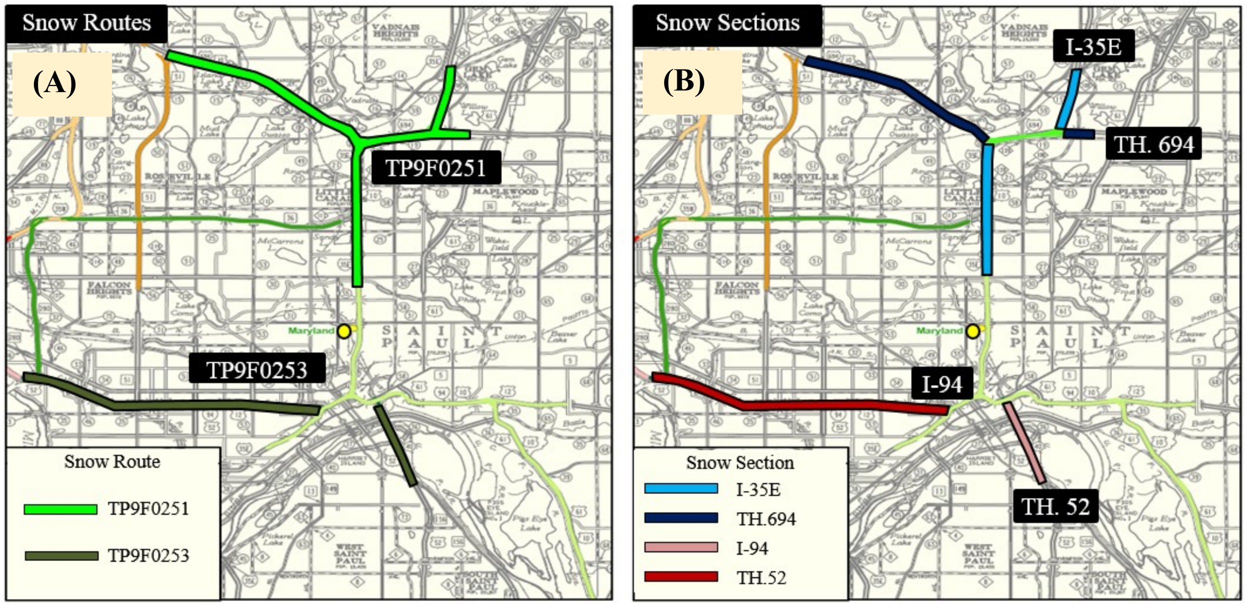

Figure 2: (A) Configurations of Snow Routes; (B) Selected Snow Sections

As shown in Table 2, the length of each of the selected snow sections is usually within 5 miles, which takes less than 5 minutes for road users to drive through under free-flow conditions. It allows the traffic data collected from the different stations within a section to be reasonably aggregated to reflect the global features of the section-wide traffic flow.

Table 2: Information of the Selected Snow Corridor

Snow Corridor	Length (miles)	Posted Speed Limit (mph)	Estimated Travel Time under the Posted Speed Limit (min)
I-35E	4.9	60	4.9
T.H. 694	4.5	60	4.5
I-94	4.7	55	5.1
T.H. 52	1.1	55	1.2

3.2. Data Collection Process and Collected Data

An overview of the dataset used in this study is shown in Figure 3 below. It consists of three types which include road maintenance/operations information, road weather information and traffic flow data.

As for the road maintenance/operations dataset, it was compiled from the PPMS report (Program and Project Management System) provided by the MnDOT. The two main types of data used in the PPMS report were the snow event start/end time and the reported bare lane regain time. Using that information, the list of snow events for this research was determined and the approximate road condition recovery time was established.

In terms of road weather condition data, it was collected from two different sources, including the *MnDOT Traveler Information* website and the Road Weather Information System (RWIS). Through the *MnDOT Traveler Information* website, CCTV images displaying real-time road conditions during snow events were collected to record significant improvements in road conditions and to capture any moments where snow plowing operations were executed within a section. This data was used to identify any traffic flow patterns during the times of individual plowing operation.

Another source of road weather data was the RWIS. Among the RWIS dataset, the daily database on the precipitation type and the variations of precipitation were accessed to identify the dry-normal days within a predetermined period. The list of the selected dry-normal days was employed to develop a dry-normal pattern which was used in the comparative analysis between snow-affected traffic patterns and dry-normal traffic patterns.

Lastly, a traffic flow dataset was collected from inductive loop detectors installed on the Metropolitan freeways in the Twin Cities. Primitive types of data in the form of vehicle counts and occupancy rates were processed to macroscopic traffic flow parameters such as flow rate, density and speed. Using those parameters, traffic patterns during both dry-normal days and snow events were developed to identify the features of snow-affected traffic flow processes during snow events. The details on the collection process for each type of data will be described in the sections to follow.

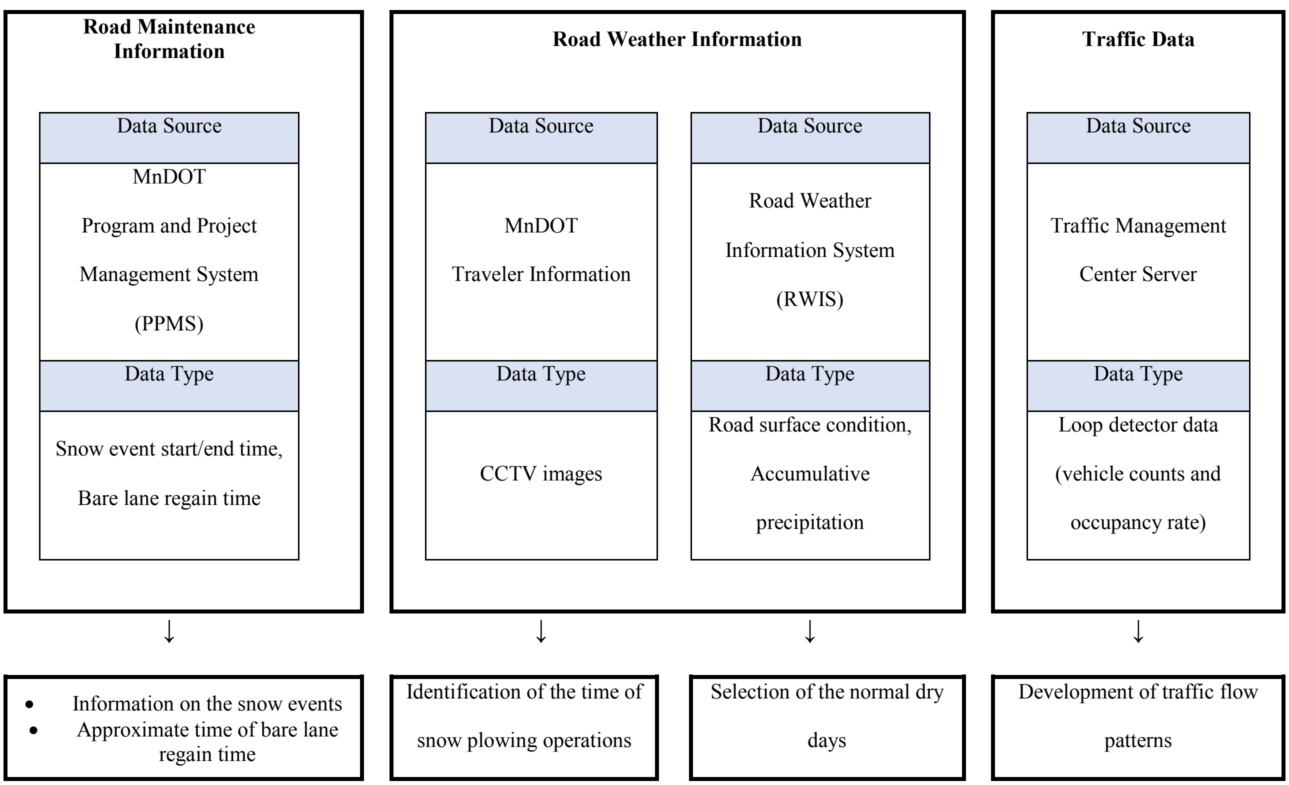

Figure 3: Overall Process of Data Collection

3.2.1. Road Maintenance Information

The PPMS reports (Program and Project Management System) provided by the MnDOT include information regarding snow events and snow plowing operations as listed below. It needs to be noted that the lane regain time occurs in 30 minute increments.

- Snow Weather Information: Plow route, Weather condition, Snow event start time, Snow event end time, and Snow event duration
- Snow Plowing Operations Information: Lane lost time, Bare lane regain time, Lane lost duration, and Recovery hours

In Table 3, 56 cases of snow events for different snow sections were selected for this research among snow events taking place between November 2011 and March 2013.

Table 3: Road Weather Information of the Selected Snow Events

Snow Route	Freeway Corridor	Snow Event Start Time		Snow Event End Time		Lane Regain Time	
TP9F0251	I-35E NB	11/19/2011(Sat)	11:00	11/19/2011(Sat)	18:30	11/19/2011(Sat)	17:30
		1/14/2012 (Sat)	10:00	1/14/2012 (Sat)	18:10	1/14/2012 (Sat)	17:00
		1/20/2012 (Fri)	6:15	1/20/2012 (Fri)	13:45	1/20/2012 (Fri)	13:15
		1/23/2012 (Mon)	1:30	1/23/2012 (Mon)	10:30	1/23/2012 (Mon)	11:00
		2/28/2012 (Tue)	7:20	2/29/2012 (Wed)	10:15	2/29/2012 (Wed)	9:09
		2/22/2013 (Fri)	1:00	2/22/2013 (Fri)	11:15	2/22/2013 (Fri)	10:30
		3/14/2013 (Thu)	3:45	3/14/2013 (Thu)	9:00	3/14/2013 (Thu)	9:30
		3/18/2013 (Mon)	4:30	3/18/2013 (Mon)	17:00	3/18/2013 (Mon)	12:00
	I-35 SB	11/19/2011(Sat)	11:00	11/19/2011(Sat)	18:30	11/19/2011(Sat)	17:30
		1/14/2012 (Sat)	10:00	1/14/2012 (Sat)	18:10	1/14/2012 (Sat)	17:00
		1/20/2012 (Fri)	6:15	1/20/2012 (Fri)	13:45	1/20/2012 (Fri)	13:15
		1/23/2012 (Mon)	1:30	1/23/2012 (Mon)	10:30	1/23/2012 (Mon)	11:00
		2/28/2012 (Tue)	7:20	2/29/2012 (Wed)	10:15	2/29/2012 (Wed)	9:09
		2/22/2013 (Fri)	1:00	2/22/2013 (Fri)	11:15	2/22/2013 (Fri)	10:30
		3/14/2013 (Thu)	3:45	3/14/2013 (Thu)	9:00	3/14/2013 (Thu)	9:30
		3/18/2013 (Mon)	4:30	3/18/2013 (Mon)	17:00	3/18/2013 (Mon)	12:00
		11/19/2011(Sat)	11:00	11/19/2011(Sat)	18:30	11/19/2011(Sat)	17:30

	TH.694 EB	1/14/2012 (Sat)	10:00	1/14/2012 (Sat)	18:10	1/14/2012 (Sat)	17:00
		1/20/2012 (Fri)	6:15	1/20/2012 (Fri)	13:45	1/20/2012 (Fri)	13:15
		1/23/2012 (Mon)	1:30	1/23/2012 (Mon)	10:30	1/23/2012 (Mon)	11:00
		2/28/2012 (Tue)	7:20	2/29/2012 (Wed)	10:15	2/29/2012 (Wed)	9:09
		2/22/2013 (Fri)	1:00	2/22/2013 (Fri)	11:15	2/22/2013 (Fri)	10:30
		3/14/2013 (Thu)	3:45	3/14/2013 (Thu)	9:00	3/14/2013 (Thu)	9:30
		3/18/2013 (Mon)	4:30	3/18/2013 (Mon)	17:00	3/18/2013 (Mon)	12:00
	TH.694 WB	11/19/2011(Sat)	11:00	11/19/2011(Sat)	18:30	11/19/2011(Sat)	17:30
		1/14/2012 (Sat)	10:00	1/14/2012 (Sat)	18:10	1/14/2012 (Sat)	17:00
		1/20/2012 (Fri)	6:15	1/20/2012 (Fri)	13:45	1/20/2012 (Fri)	13:15
		1/23/2012 (Mon)	1:30	1/23/2012 (Mon)	10:30	1/23/2012 (Mon)	11:00
		2/28/2012 (Tue)	7:20	2/29/2012 (Wed)	10:15	2/29/2012 (Wed)	9:09
		2/22/2013 (Fri)	1:00	2/22/2013 (Fri)	11:15	2/22/2013 (Fri)	10:30
		3/14/2013 (Thu)	3:45	3/14/2013 (Thu)	9:00	3/14/2013 (Thu)	9:30
		3/18/2013 (Mon)	4:30	3/18/2013 (Mon)	17:00	3/18/2013 (Mon)	12:00
TP9F0253	I-94 EB	1/14/2012 (Sat)	10:15	1/14/2012 (Sat)	18:25	1/14/2012 (Sat)	21:30
		1/20/2012 (Fri)	6:15	1/20/2012 (Fri)	13:45	1/20/2012 (Fri)	13:15
		1/23/2012 (Mon)	1:30	1/23/2012 (Mon)	10:30	1/23/2012 (Mon)	11:00
		2/28/2012 (Tue)	7:20	2/29/2012 (Wed)	10:15	2/29/2012 (Wed)	9:09
		2/22/2013 (Fri)	1:00	2/22/2013 (Fri)	10:15	2/22/2013 (Fri)	11:00
		3/18/2013 (Mon)	4:30	3/18/2013 (Mon)	17:00	3/18/2013 (Mon)	10:00
	I-94 WB	1/14/2012 (Sat)	10:15	1/14/2012 (Sat)	18:25	1/14/2012 (Sat)	21:30
		1/20/2012 (Fri)	6:15	1/20/2012 (Fri)	13:45	1/20/2012 (Fri)	13:15
		1/23/2012 (Mon)	1:30	1/23/2012 (Mon)	10:30	1/23/2012 (Mon)	11:00
		2/28/2012 (Tue)	7:20	2/29/2012 (Wed)	10:15	2/29/2012 (Wed)	9:09
		2/22/2013 (Fri)	1:00	2/22/2013 (Fri)	10:15	2/22/2013 (Fri)	11:00
		3/18/2013 (Mon)	4:30	3/18/2013 (Mon)	17:00	3/18/2013 (Mon)	10:00
	TH.52 NB	1/14/2012 (Sat)	10:15	1/14/2012 (Sat)	18:25	1/14/2012 (Sat)	21:30
		1/20/2012 (Fri)	6:15	1/20/2012 (Fri)	13:45	1/20/2012 (Fri)	13:15
		1/23/2012 (Mon)	1:30	1/23/2012 (Mon)	10:30	1/23/2012 (Mon)	11:00
		2/28/2012 (Tue)	7:20	2/29/2012 (Wed)	10:15	2/29/2012 (Wed)	9:09
		2/22/2013 (Fri)	1:00	2/22/2013 (Fri)	10:15	2/22/2013 (Fri)	11:00
		3/18/2013 (Mon)	4:30	3/18/2013 (Mon)	17:00	3/18/2013 (Mon)	10:00
	TH.52 SB	1/14/2012 (Sat)	10:15	1/14/2012 (Sat)	18:25	1/14/2012 (Sat)	21:30
		1/20/2012 (Fri)	6:15	1/20/2012 (Fri)	13:45	1/20/2012 (Fri)	13:15
		1/23/2012 (Mon)	1:30	1/23/2012 (Mon)	10:30	1/23/2012 (Mon)	11:00
		2/28/2012 (Tue)	7:20	2/29/2012 (Wed)	10:15	2/29/2012 (Wed)	9:09
		2/22/2013 (Fri)	1:00	2/22/2013 (Fri)	10:15	2/22/2013 (Fri)	11:00
		3/18/2013 (Mon)	4:30	3/18/2013 (Mon)	17:00	3/18/2013 (Mon)	10:00

3.2.2. Road Weather Information

RWIS data (http://rwis.dot.state.mn.us/)

RWIS (Road Weather Information System), committed to most of the state DOTs in the United States, is a central communication system that aims to transfer and collect field data from numerous Environmental Sensor Stations (ESS). ESS is the principal base station of weather data collection and the collected data includes both atmospheric and pavement data. Atmospheric data includes air temperature and humidity, visibility distance, wind speed and direction, precipitation type and rate, etc. Pavement data includes pavement temperature, pavement freezing point, pavement conditions (e.g., wet, icy, flooded), surface conditions, etc. It should be noted that the pavement data is primarily unique in nature and highly site-specific. Central RWIS hardware and software are used to process the observations from ESS to develop real-time casting or forecasts and disseminate road weather information in a format that can be easily interpreted by users.

In this study, daily precipitation data through all months was inspected within the same month of the snow event to select all possible “dry-normal days.” The “dry-normal day” was defined as one where the precipitation remains zero and the road surface conditions continue to be dry all day. The selected dry-normal days were used to develop an average dry-normal pattern for each snow event, which was subsequently used to identify the impact of weather events on traffic flow variations and to determine the phase change points in traffic variations.

CCTV (Closed-Circuit Television) Images

The real-time CCTV images were collected from the *MnDOT Traveler's Information* website for the selected snow sections during snow events from December 2013 to February 2014. Data was collected every 15 to 30 minutes when snow plowing operations were actively executed. However, there were some difficulties in data collection as it was only possible to manually clip an image of one spot at a time to proceed through the entire study areas in sequence. As shown in Figure 4, it was identified when snow plowing trucks were deployed and/or the significant improvements in the road conditions were made. Such information supported the analysis of traffic flow patterns at the road condition recovery periods.

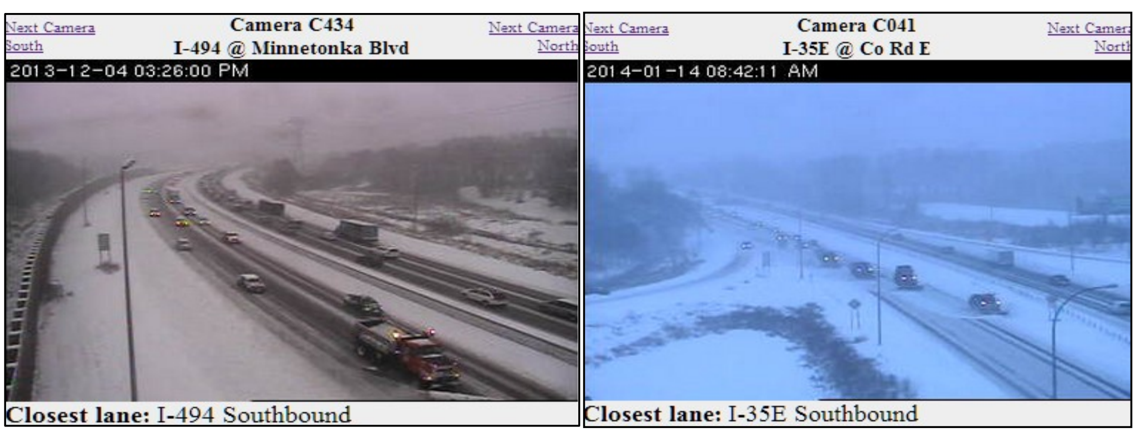

Figure 4: CCTV images of Snow Plowing Trucks in Operations within a Section

3.2.3. Traffic Flow Data

Station Traffic Flow Data

Inductive loop detectors are located on the mainline of freeways approximately every half mile and on entrance and exit ramps. The loop detectors collect information about vehicle counts and occupancy rates and report the data back to the Traffic Management Center (TMC) every 30 seconds.

That primitive form of data was accessed using the TICAS (Traffic Information and Condition Analysis System), developed at University of Minnesota Duluth to estimate the macroscopic parameters of traffic flow, e.g., flow rate (q), speed (u) and density (k). The traffic flow parameters were estimated based on the equations seen below. Then, traffic data in 30-second intervals were aggregated into 3-minute intervals to reduce the random fluctuations on the traffic patterns.

$$q\ (veh/hr) = \frac{vehicle\ counts\ (veh)}{30\ sec(\frac{1hr}{3600\ sec})}$$

Equation 4

$$k\ (veh/mi) = \frac{5280 \times Occupancy\ (\%)}{L\ (ft) + L_D\ (ft)}$$

Equation 5

$$u\ (mph) = \frac{flow\ rate\ (veh/hr)}{density\ (veh/mi)}$$

Equation 6

where,

L = Average Vehicle Length (ft)

L_D = Detector Length (ft)

Section-wide Traffic Flow Data

The station-based traffic flow data was then processed to develop a section-wide averaged data weighed by distance. The process to estimate the section-wide traffic flow parameters is demonstrated in the schematic diagram in Figure 5. The section includes the three stations, i.e., Station 1-3, of which the traffic flow parameters at time t are denoted as $q_{i,t}, k_{i,t}$ and $u_{i,t}$ when i refers to the station number. For example, Station 1 involves $q_{1,t}, k_{1,t}$ and $u_{1,t}$, Station 2 involves $q_{2,t}, k_{2,t}$ and $u_{2,t}$, and Station 3 involves $q_{3,t}, k_{3,t}$ and $u_{3,t}$ at time t.

The distance between Station i and Station i+1 was indicated as L_i. For instance, L_1 refers to the distance between Station 1 and 2, and L_2 refers to the distance between Station 2 and Station 3. As appears in the figure, each L_i was evenly divided into three segments to be allocated with different values of traffic data. For example, the left-end segment located near Station 1 was assigned with $q_{1,t}, k_{1,t}$ and $u_{1,t}$, and the right-end segment located near Station 2 was assigned with $q_{2,t}, k_{2,t}$ and $u_{2,t}$. The segment located in the middle of the three divisions was assigned with the average value of the two in both sides, or $\frac{q_{1,t}+q_{2,t}}{2}, \frac{k_{1,t}+k_{2,t}}{2}$ and $\frac{u_{1,t}+u_{2,t}}{2}$. A similar process was repeated for L_2 as in the figure shown. Then the allocated traffic flow value for each segment was multiplied by the length of the corresponding segment. Next, the results for all segments were summed up within the entire section.

Then, the result was divided by the total length of the section to calculate the section-wide average traffic flow data. The calculation is provided in Equation 7-Equation 9 below.

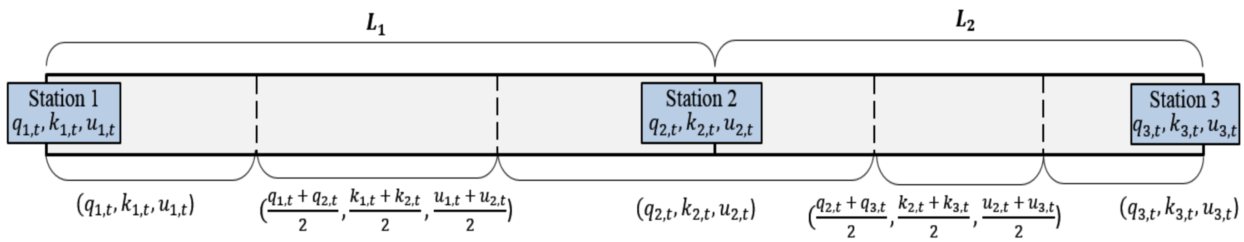

Figure 5: Process to Calculate Section-wide Traffic Data

$$q_{c,t} = \sum_{i=1}^{N-1} \frac{1}{3} L_i \cdot \left(q_{i,t} + \frac{q_{i,t} + q_{i+1,t}}{2} + q_{i+1,t}\right) \Big/ \sum_{i=1}^{N-1} L_i$$

Equation 7

$$k_{c,t} = \sum_{i=1}^{N-1} \frac{1}{3} L_i \cdot \left(k_{i,t} + \frac{k_{i,t} + k_{i+1,t}}{2} + k_{i+1,t}\right) \Big/ \sum_{i=1}^{N-1} L_i$$

Equation 8

$$u_{c,t} = \sum_{i=1}^{N-1} \frac{1}{3} L_i \cdot \left(u_{i,t} + \frac{u_{i,t} + u_{i+1,t}}{2} + u_{i+1,t}\right) \Big/ \sum_{i=1}^{N-1} L_i$$

Equation 9

where,

i = Station number

N = Number of stations within a section

L_i = Length of the segment between Station i and i+1

$q_{c,t}$ = section-wide flow rate at time t

$k_{c,t}$ = section-wide density at time t

$u_{c,t}$ = section-wide speed at time t

$q_{i,t}$ = flow rate of Station i at time t

$k_{i,t}$ = density of Station *i* at time t

$u_{i,t}$ = speed of Station *i* at time t

Smoothing Process

To extract a primary pattern of traffic flow process, the section-wide traffic data was then prepared with a smoothing process using the moving average method. To reduce lag time between the original data and the smoothed data, a set of 3 minutes before and after each time point was averaged as expressed in the following set of formulas. The resulting patterns are shown in Figure 7 below. The subsequent traffic flow data of smoothed patterns is used through the pattern analysis in this research.

$$q^*_{c,t} = \frac{1}{(2m+1)} \sum_{i-m}^{i+m} q_{c,t}$$

Equation 10

$$k^*_{c,t} = \frac{1}{(2m+1)} \sum_{i-m}^{i+m} k_{c,t}$$

Equation 11

$$u^*_{c,t} = \frac{1}{(2m+1)} \sum_{i-m}^{i+m} u_{c,t}$$

Equation 12

where,

$q^*_{c,t}$ = smoothed section-wide flow rate at time t

$k^*_{c,t}$ = smoothed section-wide density at time t

$u^*_{c,t}$ = smoothed section-wide speed at time t

$q_{c,t}$ = section-wide flow rate at time t

$k_{c,t}$ = section-wide density at time t

$u_{c,t}$ = section-wide speed at time t

m = number of time intervals included in the moving average process, i.e., 1 for using 3min data

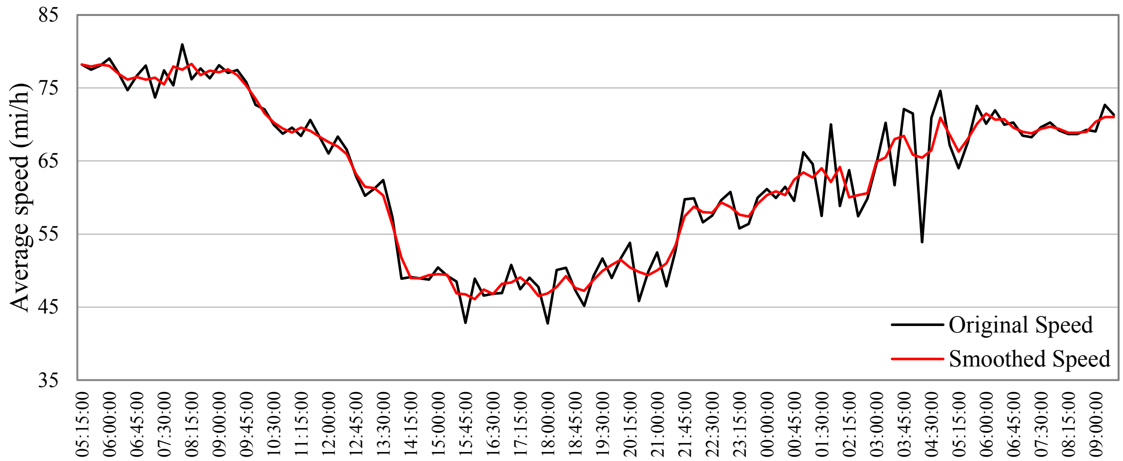

Figure 6: Smoothing Process using 3 minute Speed Variations

CHAPTER 4: ANALYSIS OF TRAFFIC FLOW PROCESS DURING SNOW EVENTS USING SECTION-WIDE FUNDAMENTAL DIAGRAMS

In Chapter 4, the traffic flow process during snow events will be analyzed using the following terms:

4.1 Development of Section-wide Fundamental Diagrams (SFD) for Snow Sections

4.2 Analysis of Section-wide Traffic Flow Process during now Events using SFD

4.3 Identification of Phase Change Points of Traffic Flow Process

The Section-wide Fundamental Diagrams (SFD) for the snow sections will be developed in Chapter 4.1. The SFD will be used in analysis of traffic flow behavior during snow events in Chapter 4.2. Based on the result of analysis, the phase change points within the traffic flow variations will be identified in Chapter 4.3.

4.1. Development of Section-wide Fundamental Diagrams (SFD) for Snow Sections

In Chapter 4, Section-wide Fundamental Diagrams (SFD) for the snow sections will be developed using the section-wide average traffic flow data. Based on the comparative analysis with the Station Fundamental Diagrams within a consistent section, it was observed that SFD well represented the characteristics of the section-wide traffic flow by reproducing a similar traffic flow process to the individual stations within the section.

Figure 8 shows the typical patterns of SFD for Snow Section I-35E SB during dry-normal days, and Figure 9 shows the Station Fundamental Diagram patterns for the selected stations within the consistent snow section. It was observed that the traffic flow process in SFD demonstrated comparable behaviors with the one in Station Fundamental Diagrams with the following points:

- The QK pattern of SFD showed a triangular-shaped curve consisting of two types of vectors. One vector was the free-flow side of the curve, and the second vector was the side of the congested condition which was created by placing the vector connected to the jam density. The congested vector had a negative slope which implies that the higher the density, the lower the flow.
- The UK pattern of SFD was linear with a negative slope by indicating the relations where the density increased and the speed decreased.
- In both patterns of SFD, the state of traffic flow changed from stable to unstable at a critical traffic density.
- In both patterns of SFD, the points of interest in traffic flow variations were located at a similar time point. The points of interest include the speed-reduction starting point, the maximum flow-rate point, the congestion-recovery-starting point, and the free-flow-recovery point.

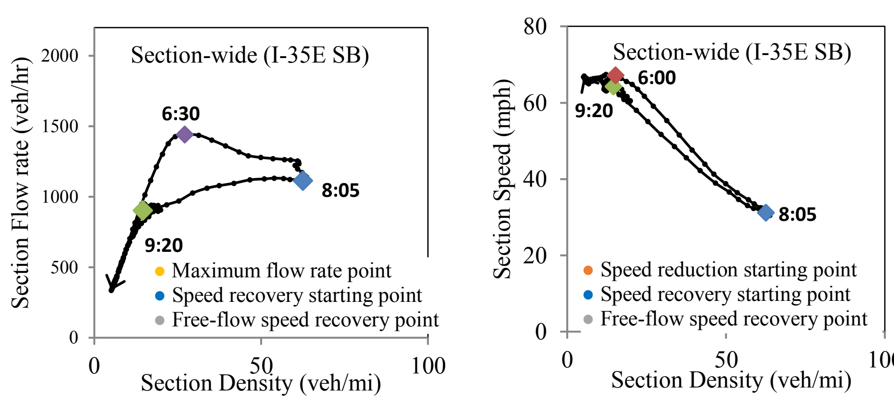

Figure 7: Section-wide Fundamental Diagrams of the Snow Section of 35E SB during Dry-Normal Day (December 13, 2012, 5:00-22:00)

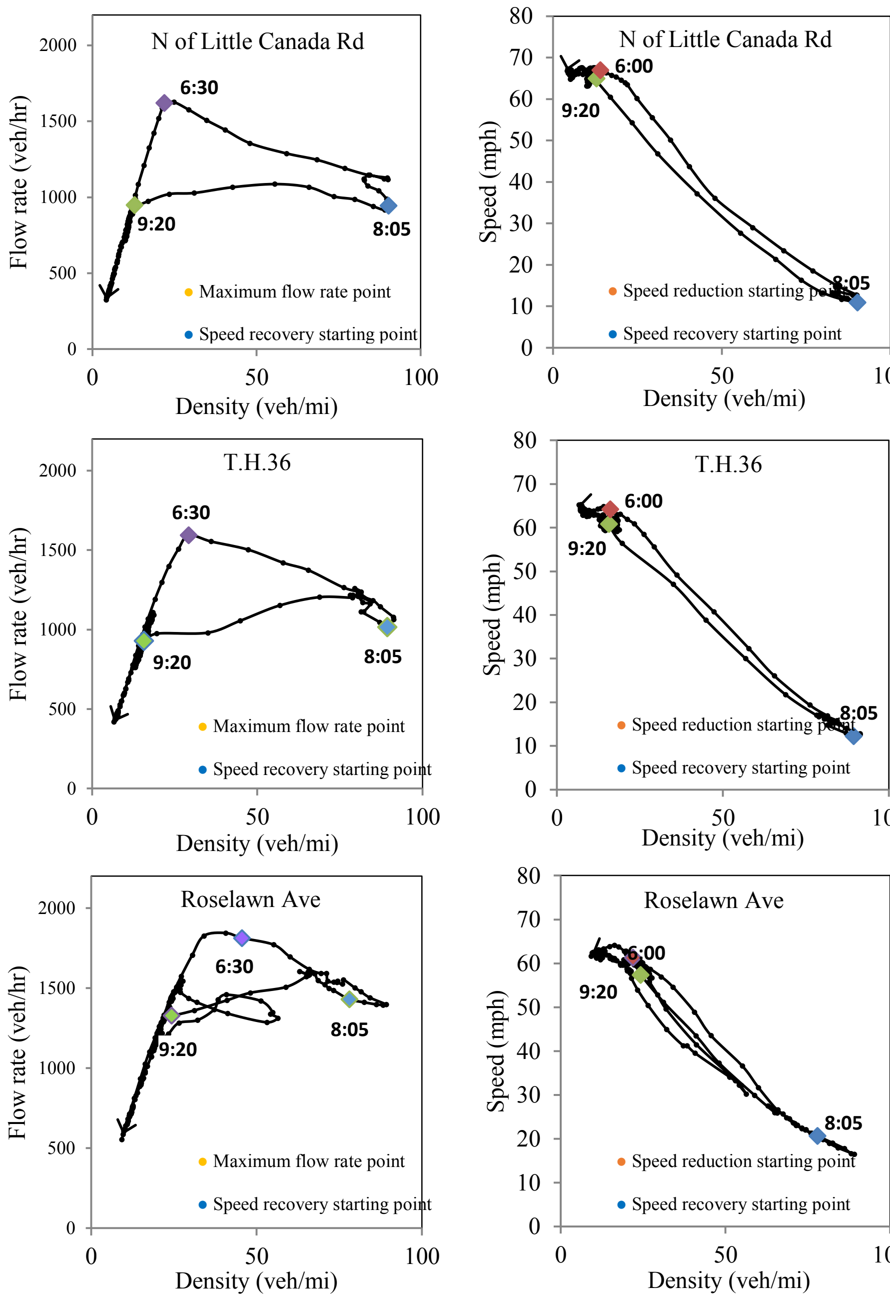

Figure 8: Station Fundamental Diagrams of the Selected Stations within the Snow Section of 35E SB during Dry-Normal Day (December 13, 2012, 5:00-22:00)

Based on these observations, SFDs reasonably reflected the capability of a road system within a section in a similar way represented in the Station Fundamental Diagrams to understand the traffic flow behavior at a particular point. However, it was required of the extended understandings of the values of the maximum flow rate in the SFDs. The maximum flow rate of the SFD indicates the traffic throughput that a section can accommodate in a given time period, being different from the maximum number of vehicles which can pass by a point in a given time period. It was observed that the maximum flow rate of SFD was determined by the flow rate of the bottleneck within the section as the bottleneck controlled the throughput of the entire section.

4.2. Analysis of Section-wide Traffic Flow Process during Snow Events

In this section, section-wide traffic flow patterns during snow events will be analyzed using a speed variations plot and the SFDs developed in the previous section. This chapter will consist of the following sections:

- 4.2.1 Speed variations process during snow events
- 4.2.2 Speed reduction period
- 4.2.3 Road condition recovery period
- 4.2.4 Normal traffic pattern recovery period
- 4.2.5 Identification of phase change points

In Section 4.2.1, general descriptions of the speed variation process during snow events will be represented. Based on the results, three types of periods within the speed variations will be determined including: speed reduction period, road condition recovery period and normal speed recovery period. Through Sections 4.2.2 to 4.2.3, detailed analyses on the traffic flow patterns will be conducted for each distinctive period in the speed variations. In Section 4.2.5, the six phase change points will be determined in the traffic flow process during snow events.

4.2.1. Speed Variations Process during Snow Events

Based on the analysis of snow-affected traffic speed process, two types of patterns were identified with different conditions of traffic volumes in the sections. The typical pattern of snow-affected traffic flow variations during off-peak times is shown in Figure 9 and the case during peak times is shown in Figure 10.

In both cases, speed began to deviate from the dry-normal pattern after the snow event was initiated. Speed reached its minimum level as road conditions became worse. Speed increased as road conditions started to improve, due to the snow plowing operations executed within the given section. The durations and the patterns of the recovery were distinct in nature, depending on the methods of snow plowing operations and the variations in precipitation.

As shown in Figure 9, the bare lane-regain conditions allowed the speed to continue increasing up to the posted speed limit of the section as long as traffic was not congested.

After that point, speed remained at sustained levels for a while above the speed limit, but less than the dry-normal speed when wet conditions were obtained for the section. In turn, speed increased to dry normal levels when the road eventually became dry.

On the contrary, when traffic was congested during road recovery, speed began to decrease before reaching the posted speed limit because of traffic congestion, as shown in Figure 10. This type of case imposes difficulties in estimating road surface conditions.

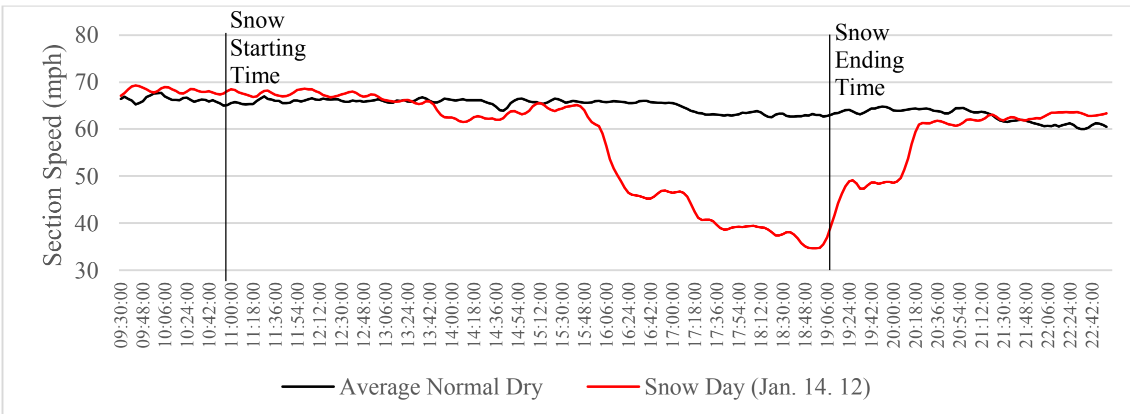

Figure 9: Phase Change Points in Traffic Flow Variations of 94 EB Snow Section during snow events on January 14, 2012 (Normal: black / Snow: red)

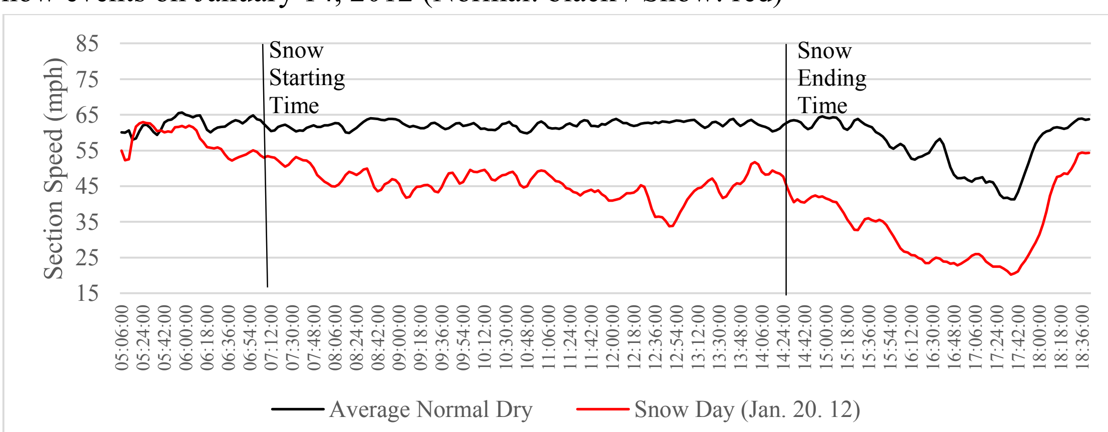

Figure 10: Phase Change Points in Traffic Flow Variations of 94 EB Snow Section during snow events on January 20, 2012

For each case, the above patterns were represented in the schematic diagrams in Figure 11 and Figure 12 below. It should be noted that the road condition recovery process cannot only be identified in the speed variations when traffic is congested during road recovery. The traffic flow patterns during three types of periods will be discussed in greater detail in the following sections.

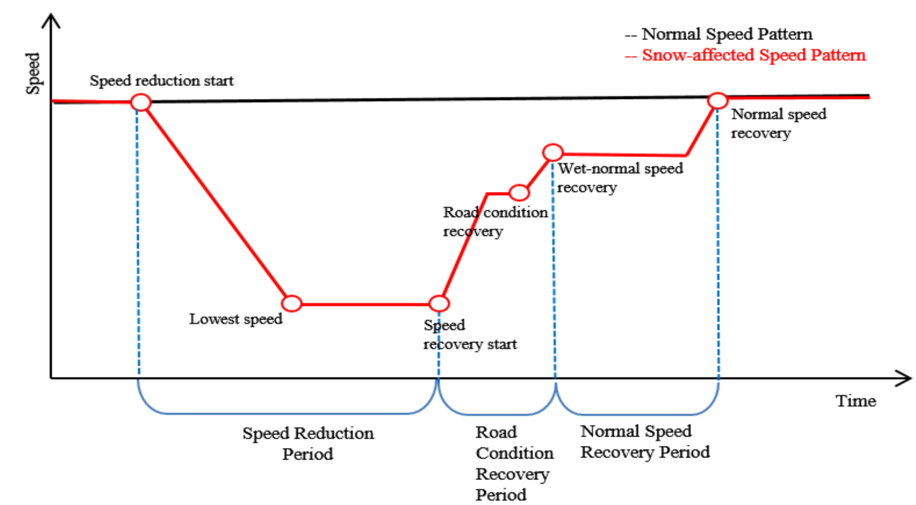

Figure 11: General Process of Snow-affected Speed Variations during Off-peak Time

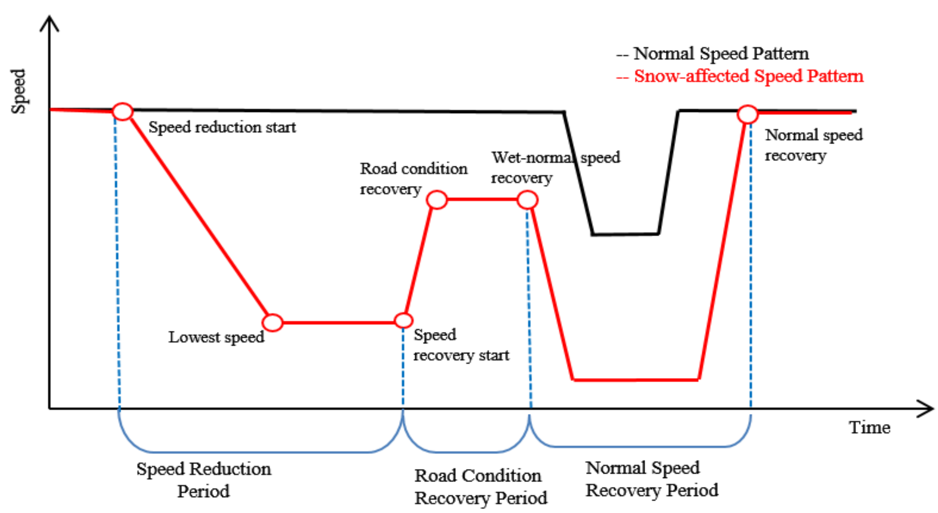

Figure 12: General Process of Snow-affected Speed Variations during On-peak Time

4.2.2. Traffic Flow Process during the Speed Reduction Period

Within the stage of speed reduction, three types of patterns were identified depending on traffic volumes and precipitation intensity at the beginning of snow events. Each type of reduction pattern will be discussed in the sections to follow.

Type 1 Reduction Pattern: Both K and U decrease

Type 1 Reduction Pattern was characterized by the traffic flow behaviors that both speed and density decreased after the speed reduction starting point, as shown in Figure 13. This type was primarily observed in the case with diminishing traffic volumes during off-peak times. The patterns were observed regardless of the intensity of snow precipitation.

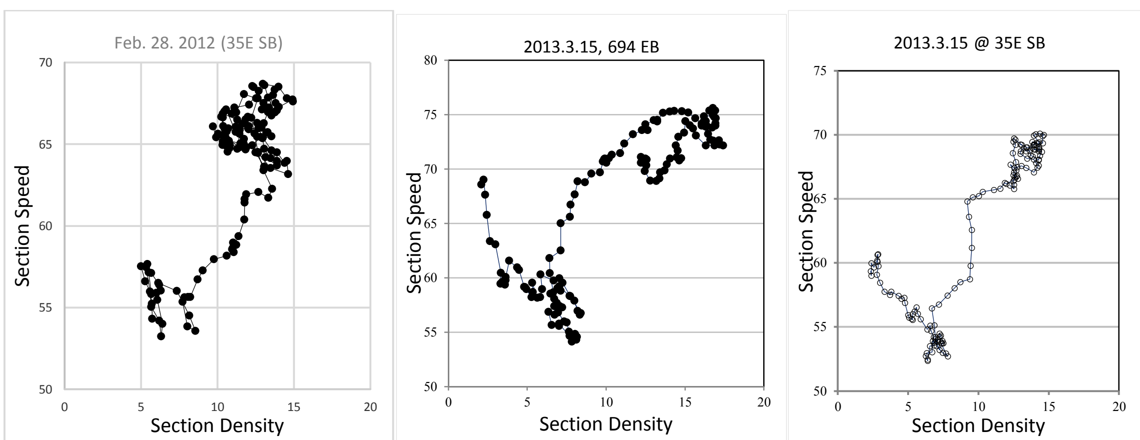

Figure 13: Type 1 Reduction Pattern: Speed decreases with decreasing density

Type 2 Reduction Pattern: K increases and U decreases

The Type 2 Reduction Pattern was characterized by traffic flow behaviors that speed decreased with increasing density after the speed reduction starting point as shown in Figure 14. After the speed reduction starting point, it was observed that the density increased even at similar levels of traffic volume variations within the section. This was caused by the tendency of drivers to attempt to maintain an original level of flow rate. However, in most cases, a significant amount of speed reduction resulted in a decrease in flow rate even at increased density.

The Type 2 Pattern was predominantly observed during snow event cases with light precipitation, which explains the tendency of drivers under light snow precipitation to avoid hesitation in decreasing gap distance from the preceding vehicle in an attempt to maintain the original throughput in compensation of reduced speed due to snow.

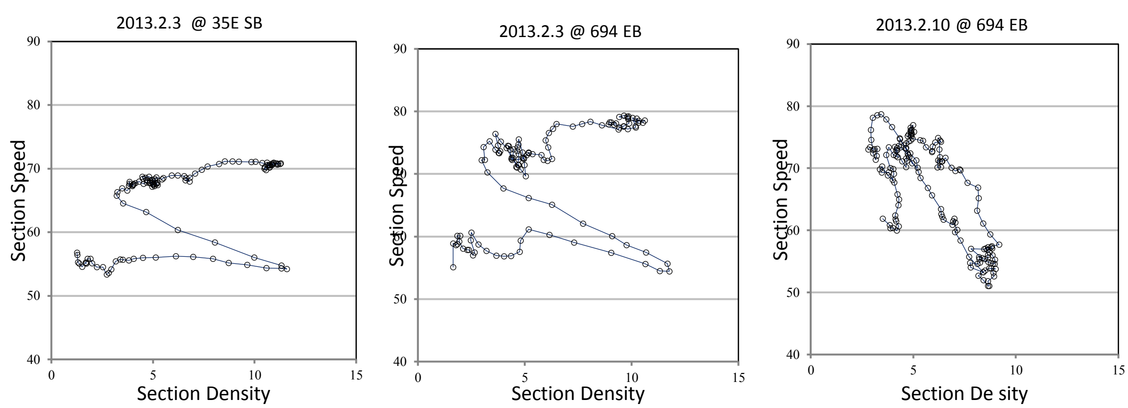

Figure 14: Type 2 Reduction Pattern: Speed decreases with increasing density

Type 3 Reduction Pattern: K sustains while U increases

The Type 3 Reduction Pattern was characterized by traffic flow behaviors where speed decreased with sustaining density under conditions of heavy precipitation. This type of pattern was predominantly captured during the high intensity of snow events, i.e., relatively lower average temperatures and a high level of accumulation of snow on the road.

Figure 15 shows the typical patterns of Type 3 Reduction Pattern. As shown in the figure, it was observed that after the speed reduction starting point, the density level sustained its value during speed reduction. This traffic flow pattern reflects the drivers' behavior against the onset of significant snow events where drivers tend to maintain gap distance from the preceding vehicle while they decrease their speed because of snow. During intense weather conditions, drivers are prone to become cautious and hesitant, in order to maintain gap distance from the preceding vehicles, which resulted in the vertical decreasing speed reduction pattern in the SFD.

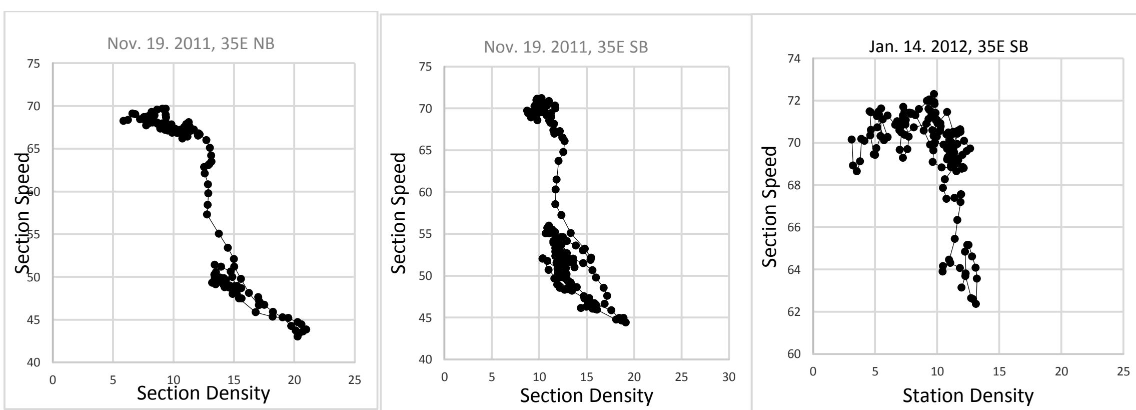

Figure 15: Type 3 Reduction Pattern: Speed decreases with sustaining density

Based on the analysis, three types of speed reduction patterns and the factors resulting from each type were identified, as shown below. In the schematic diagrams in Figure 16, if traffic volume was trivial, both speed and density decreased regardless of precipitation. When traffic volume within the section was significant, two different types of reduction patterns were identified. If snow precipitation was not significant, speed decreased while density increased. If snow precipitation was significantly intense and causing rapidly degenerating road conditions, vertical decrease patterns were observed in the SFD.

- Type 1 Reduction Pattern – Both K and U decrease: Under low traffic volumes regardless of precipitations.
- Type 2 Reduction Pattern – K increases while U decrease: Under significant traffic volumes with light precipitation.
- Type 3 Reduction Pattern – K sustains while U decreases: Under significant traffic volumes with heavy precipitation.

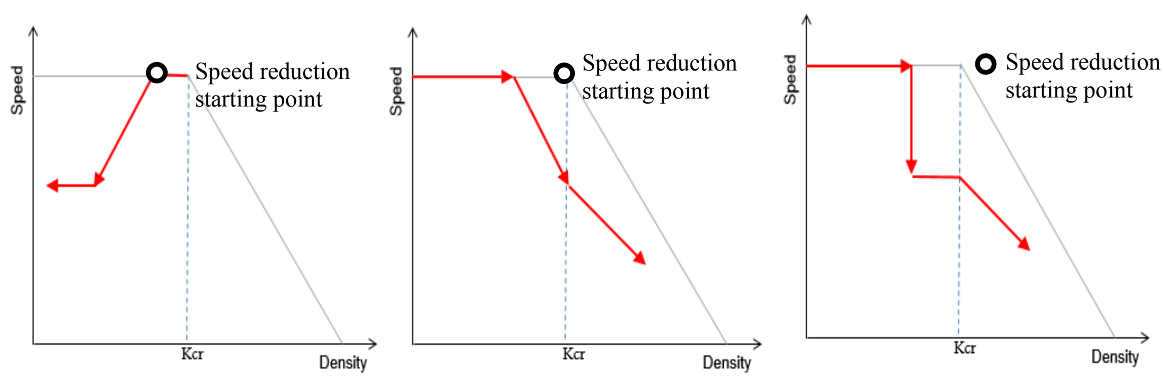

Figure 16: Schematic Diagrams of the Reduction Pattern Types: Type 1 (Left); Type 2 (Middle); Type 3 (Right)

4.2.3. Traffic Flow Process during Road Condition Recovery Period

Within the speed recovery stage, particularly until road conditions were bare, traffic flow patterns were mainly determined by the snow plowing operations executed within the snow sections. The effect of snow plowing operations on traffic flow is represented in the form of a disturbance at the entry time point of the snow plowing truck into the section. As the snow plowing truck left the section, it was observed that traffic flow improved, which was attributed to the recovery of road conditions.

In this section, SFD patterns during the speed recovery stage, especially from the recovery starting point to the road condition recovery time will be analyzed to identify the patterns of snow plowing operations. CCTV images were employed to identify the snow plowing time points for the snow section in question.

Three types of disturbance patterns were observed at the time of snow plowing operations. Those disturbance patterns included a loop-disturbance pattern, a density-disturbance pattern and a vertical-increasing-disturbance pattern. A traffic flow pattern of each disturbance type will be identified in the sections to follow. Eventually, the traffic pattern at the bare lane regain point will be identified to select the road condition recovery point among the multiple points of the snow plowing patterns during the speed recovery stage.

Loop Disturbance Pattern

In a significant number of cases, closed loop patterns were observed in the SFDs at the time of snow plowing operations as shown in Figure 17 through Figure 20 below. Also, as appears in Figure 21, the SFDs of snow events during the past 3 years included similar loop patterns closely located to the bare lane regain times reported by snow plow operators.

Among the loop-disturbance patterns, the two different cases occurring in the opposite direction of the loop were identified. One type was characterized by a counter-clockwise loop and another type was characterized by a clockwise loop.

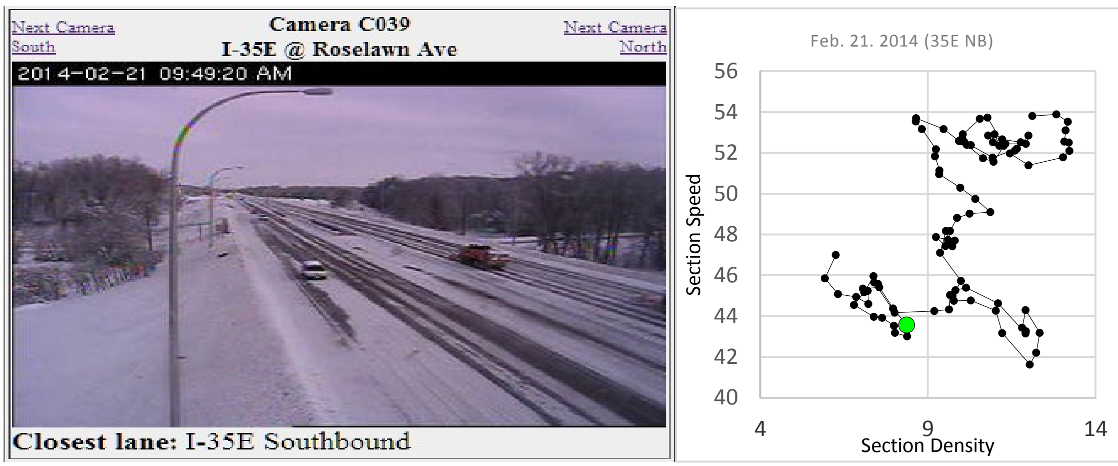

Figure 17: Snow plowing truck in Snow Section I-35E SB and the loop disturbance pattern in the SFD

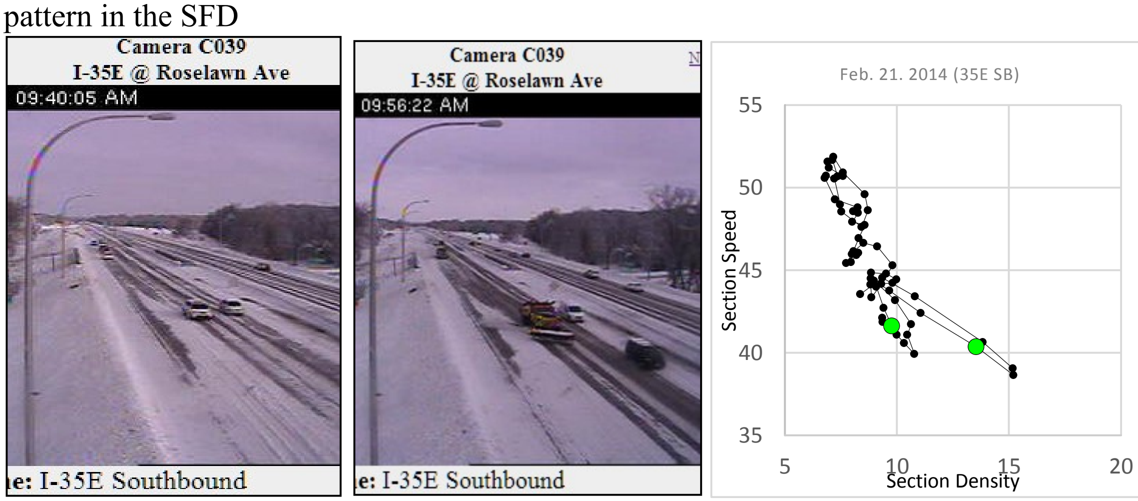

Figure 18: Consecutive operations by snow plowing trucks in Snow Section I-35E SB and the two loop disturbance patterns in the SFD

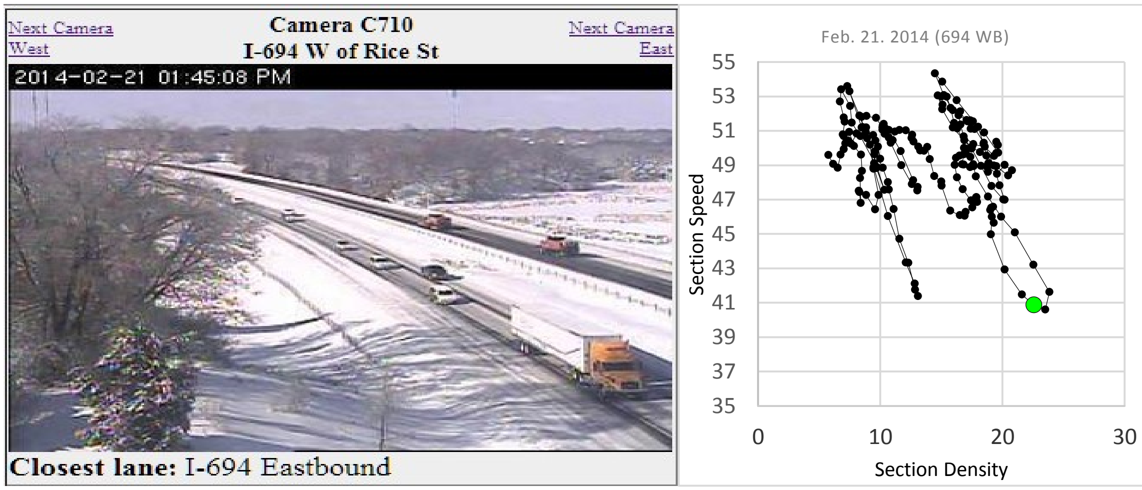

Figure 19: Snow plowing truck in Snow Section 694 EB and the loop disturbance pattern in the SFD

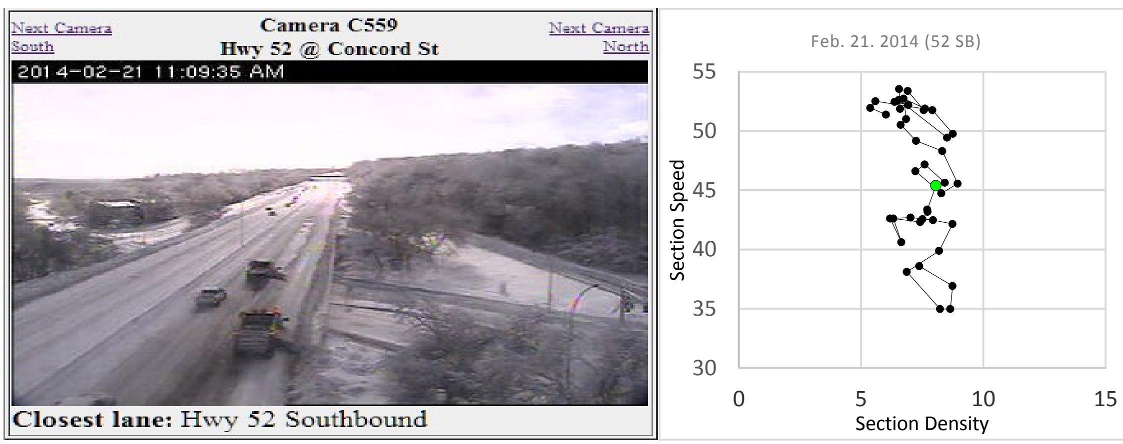

Figure 20: Snow plowing truck in Snow Section 52 SB and the loop disturbance pattern in the SFD

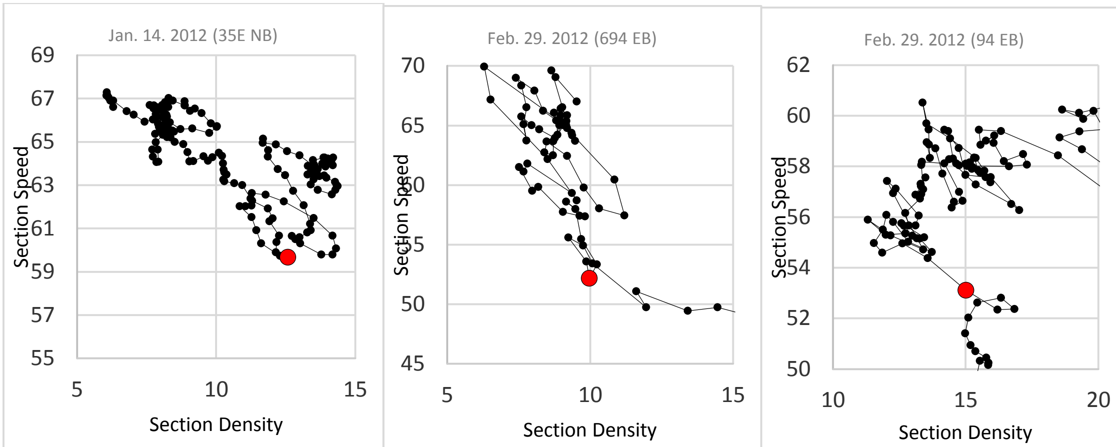

Figure 21: Last loop pattern before reaching the posted limit appeared in the UK

Counter-Clockwise Loop Disturbance Pattern

One type of loop disturbance pattern featuring a counter-clockwise rotation appears as in Figure 22. The counter-clockwise loop pattern was generated as speed began to decrease while density decreased, which was followed by density increases in the subsequent time intervals. Such speed reductions returned to increased levels while density decreased so that the UK pattern returned to the initial point of the loop pattern which was followed by the speed increase pattern in a more rapid rate than before the loop.

The counter-clockwise loops were frequently found in cases where traffic volume was not significant within the snow section at the point of snow plowing operations. As illustrated in Figure 23, when traffic volume within the snow section was not significant, the downstream traffic prior to the snow plowing truck will soon depart the section and will leave the downstream section the low density of vehicles. Until the platoon following the snow plowing truck progressed up to a certain point, the section-wide density parameters will be reduced due to the effect of the empty downstream. As the platoon advances along the section, the section-wide density will start to increase. The time point where speed begins its recovery after the loop pattern represents the time where a snow plowing truck departs the snow route, which after the upstream traffic flow experiences a transferring phase where they begin to increase their speed until they reach a speed that the improved road conditions can accommodate.

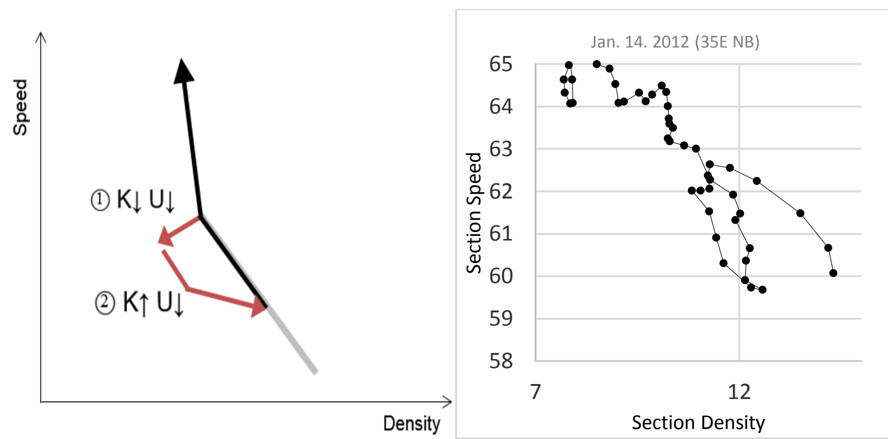

Figure 22: Schematic Diagram of typical pattern of the counter-clockwise loop pattern

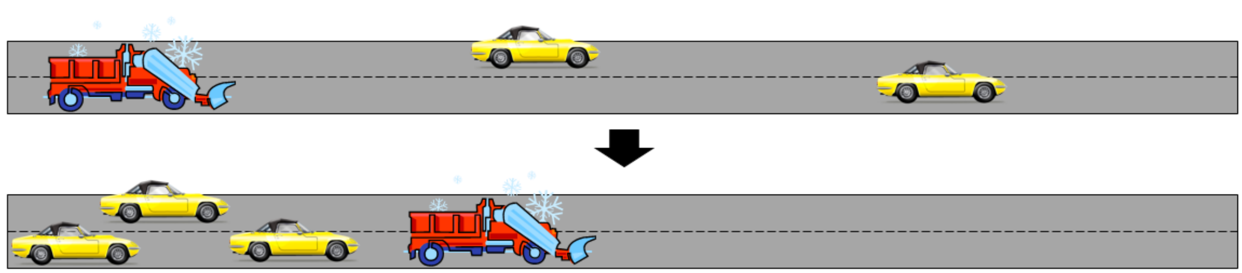

Figure 23: Impact of snow plowing operations under the insignificant traffic volumes within the section

Clockwise Loop Pattern

Another type of loop disturbance pattern is characterized by a clockwise rotation, as shown in Figure 23. The clockwise loop pattern was generated as speed started to decrease while density increased, which was followed by a decrease in density in the subsequent intervals. Such speed reduction returned to an increased level while the density decreased so that the UK pattern returned to the initial point of the loop pattern. This was followed by the speed increase pattern in a more rapid rate than before the loop.

The clockwise loops were commonly observed in cases where traffic volume was significant within the snow section within the area of snow plowing operations. As illustrated in Figure 24, when traffic volume is significant at the moment of entry of snow plowing truck into the snow route, the platoon following the snow plowing truck will only increase the density with the reduction of speed. At the point of exit of a snow plowing truck, density started to decrease and speed began to increase. Having passing the transition period to adjust to the improved road conditions, speed shows a more rapid rate of increase in the UK diagram.

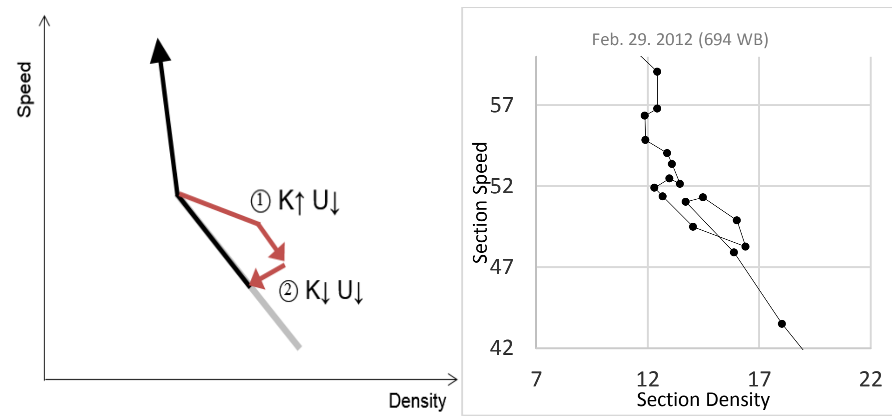

Figure 24: Schematic Diagram of typical pattern of the clockwise loop pattern

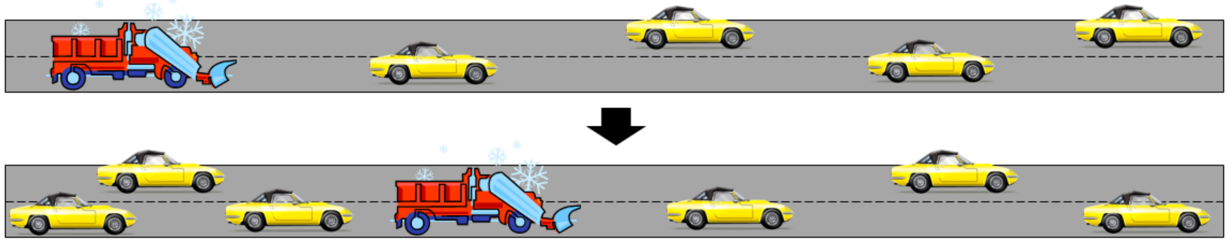

Figure 25: Impact of snow plowing operations under significant traffic volume within the section

Density Disturbance Pattern

The snow plowing operations resulted in another type of disturbance pattern which was characterized by a fluctuation in density while speed continues to increase or sustain, which is followed by a rapid increase in speed.

Figure 26 includes two CCTV images captured in succession that showed significant improvements in road conditions. The SFD in the figure involves the Density-disturbance pattern at the time when snow plowing operations were assumed to be executed.

It should be mentioned that the Density-disturbance pattern was differentiated from the loop pattern since speed was only increased or sustained, but did not decrease significantly. This type of disturbance pattern resulted when the downstream traffic flow prior to the snow plowing truck maintained a similar speed with the platoon following the snow plowing truck. In this case, the section-wide speed did not necessarily decrease because of the snow plowing trucks. As shown in Figure 27, the SFDs of the snow events in the past 3 years included similar patterns to the Density-disturbance pattern during the time interval between the speed recovery starting point and the road condition recovery point.

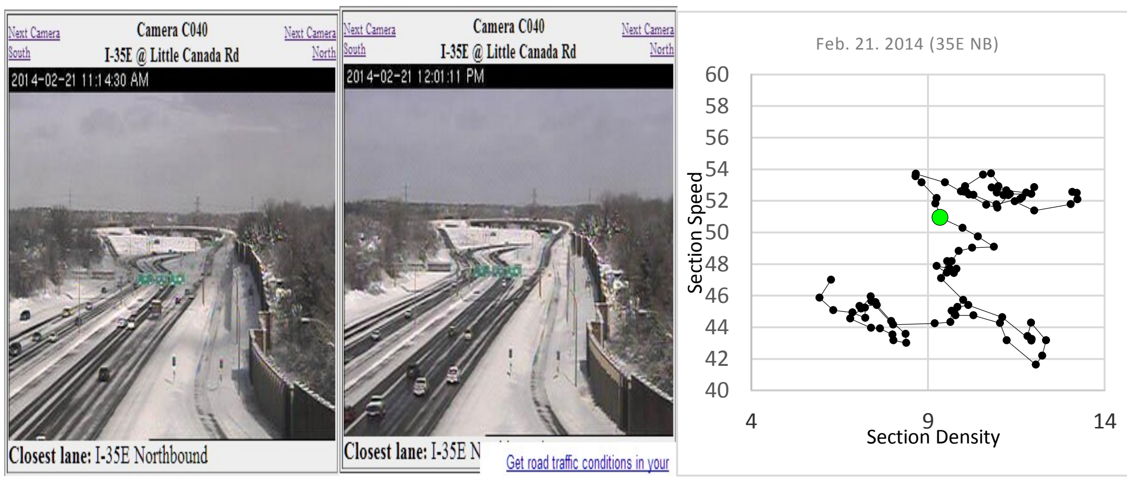

Figure 26: Road condition improvement due to Snow plowing operation executed on I-35E NB route. The density-disturbance pattern in SFD

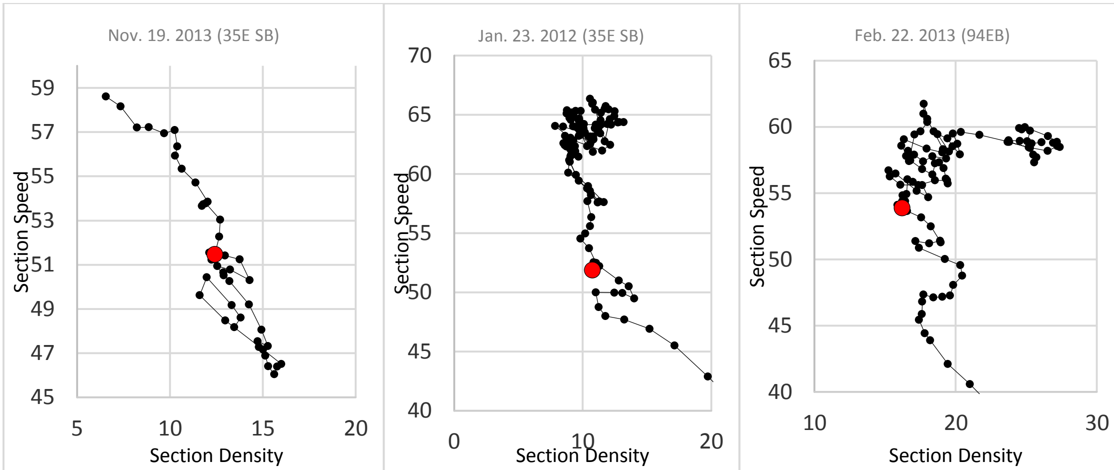

Figure 27: Density-disturbance pattern appeared in UK plots before reaching the posted speed limit

Vertical Increasing Disturbance Pattern

In several cases, as appears in Figure 28, the SFDs of the snow events in the past 3 years exhibited a consistent type of disturbance pattern near the reported bare lane regain time. This type of pattern was characterized by stagnant speed before speed started to increase rapidly for a significant amount of time. At the time of entry of snow plowing truck, if traffic volume was trivial, the snow plowing operations would not impose any significant impact on density, as the snow plowing truck-following platoon would not even be created because of trivial traffic volumes. However, even though density decreased, speed showed sustaining patterns for a significant time, which was a result of the low speed of the platoon. After the snow plowing truck exited the snow section, speed began to increase rapidly while demonstrating a vertical pattern of transition interval until reaching a speed level that the improved road environment could accommodate.

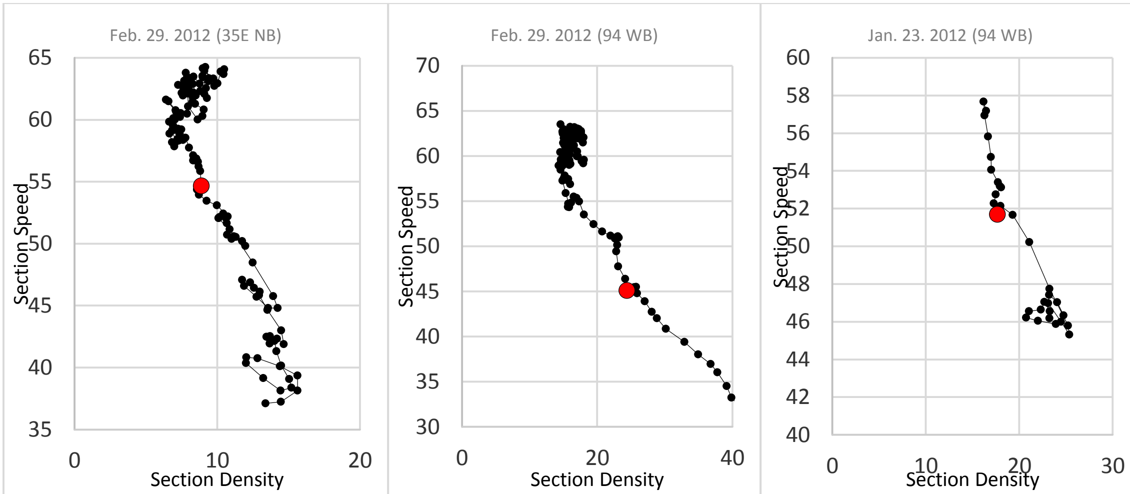

Figure 28: Vertical increasing pattern appeared in UK plots before reaching the posted speed limit

Determination of Road Condition Recovery Point

The disturbance patterns, such as the loop-disturbance pattern and the density-disturbance pattern, were possibly created because of the short time of variation in traffic volumes entering and exiting the snow section. To identify and filter out such types of disturbance patterns, the variations of the number of vehicles within a section was closely examined.

The number of vehicles within a section was estimated using the density values weighed by the distances that appear in Figure 29. The formula used to calculate the measurement of the number of vehicles was provided in Equation 13.

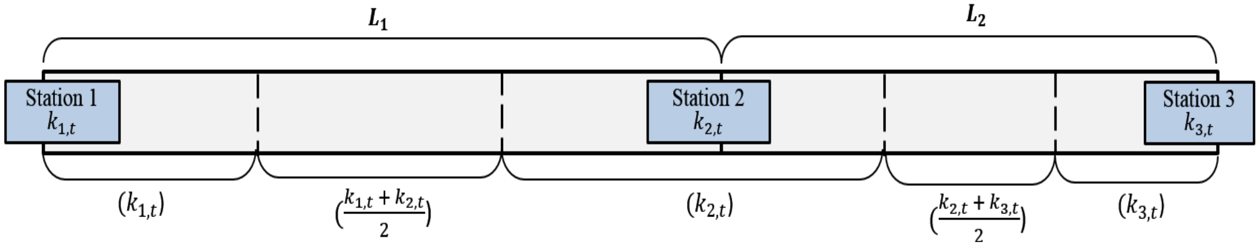

Figure 29: Distance weighted density values assigned for the segments

$$V_t = \sum_{i=1}^{N-1} \frac{1}{3} L_i \cdot (k_{i,t} + \frac{k_{i,t} + k_{i+1,t}}{2} + k_{i+1,t})$$

Equation 13

where,

V_t = Number of vehicles within a section at time t

i = Station number

N = Number of stations within a section

L_i = Length of the segment between Station i and i+1

$k_{c,t}$ = section-wide density at time t

$k_{i,t}$ = density of Station i at time t

Figure 30 shows an example case where two disturbance patterns were identified in the SFD. The disturbance patterns included the loop disturbance pattern tagged with (A) and the density-disturbance pattern tagged with (B). The variations in the number of vehicles at those two points were examined to identify any impact from the traffic variability on those two patterns, as shown in Figure 31. It was observed that the (B) was located at the point where traffic volume started to reduce meaningfully, which allowed the speed to increase in a rapid rate after that point. On the contrary, the (A) was located at the point where traffic volumes remained consistent.

In this case, it was identified that the density-disturbance pattern at (B) was caused by a reduction in traffic flow, and the loop-disturbance pattern at (A) was caused by snow plowing operations after speed started to increase.

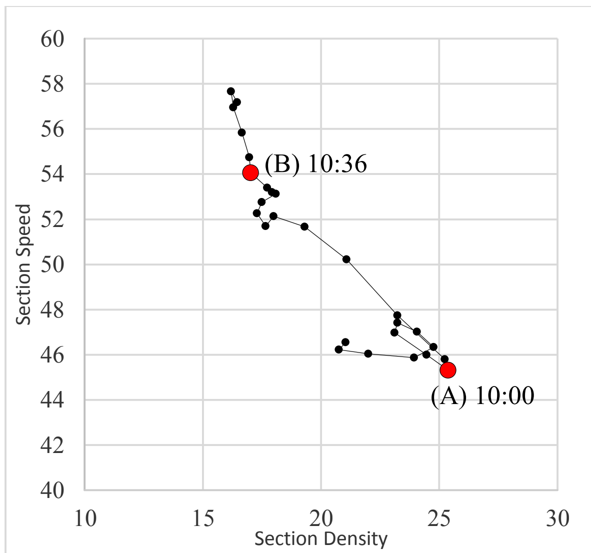

Figure 30: Two disturbance patterns identified in the SFD among which (B) were results of traffic flow variability (January 23. 2012 in I-94 WB Section)

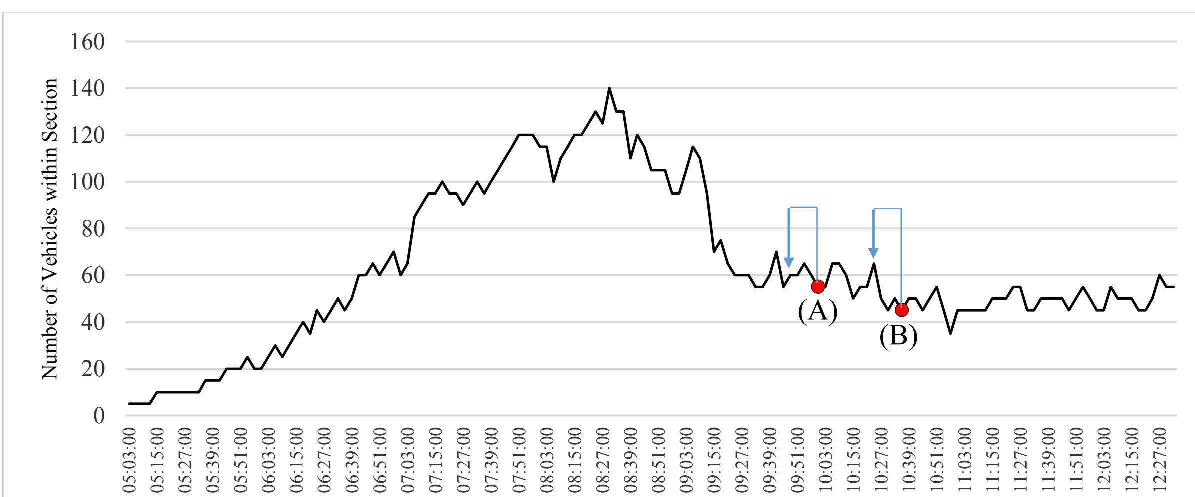

Figure 31: Variations in the number of vehicles within a section where (B) involved a traffic volume variability

Once the traffic flow disturbance patterns were screened to only leave the snow plowing operations patterns, the road condition recovery point was identified on the last snow plowing pattern before reaching the posted speed limit. If traffic was congested during the speed recovery stage, the road condition recovery point was identified on the last snow plowing pattern before reaching the Wet-Normal Recovery point where traffic flow started to recover its fundamental patterns under wet road conditions. Figure 32 displays example cases showing the selected road condition recovery point marked with red dots. It should be noted that the road condition recovery points were determined before reaching the posted speed limit point which were marked with blue crosses in the SFDs.

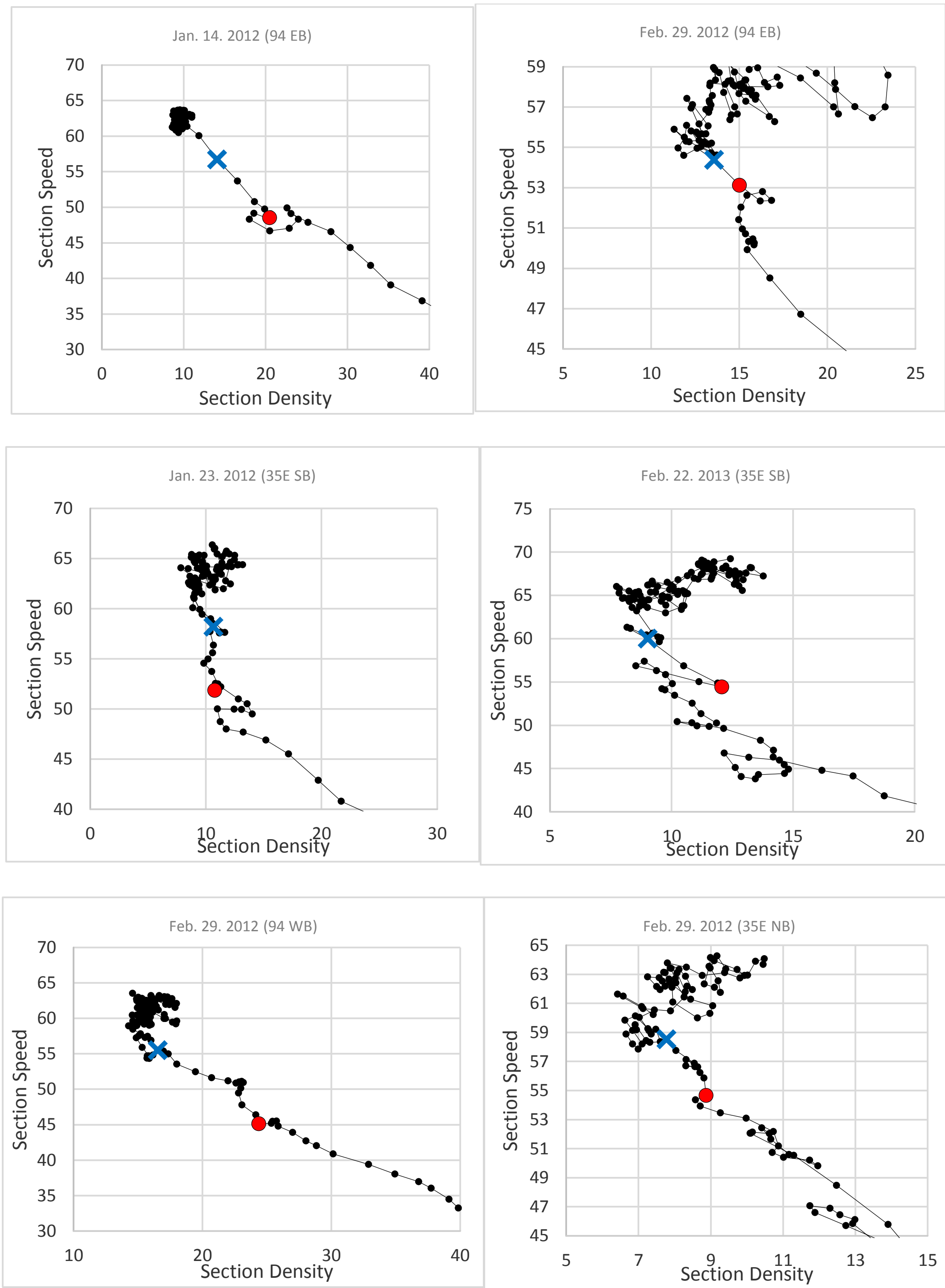

Figure 32: Selection of road condition recovery points before reaching the posted speed limit

4.2.4. Traffic Flow Process during Normal Traffic Pattern Recovery Period

According to the guidelines of the MnDOT, the bare lane regain time indicates being free of snow within the wheel path with less than 1 inch of snow on the outer edges of the wheel path. It is at this point where drivers begin to feel comfortable enough to increase speed to the posted speed limit. It should be noted that the bare lane conditions do not necessarily signify that the road is fully cleared of snow, i.e., there still exists some remaining snow on the outer edges of the wheel path and the snow mounts on the shoulders of the road. In the CCTV images, it was observed that snow plowing operations continued removal even after the bare lane was regained to fully clear out the driving lanes.

When the entire driving lane was recovered and free of snow, it was observed that the traffic flow patterns did not immediately recover the dry-normal pattern because of wet road environments. Instead, the SFD patterns started to exhibit the fundamental relationship patterns of which the speed level was lower than the dry-normal pattern. Such a point was denoted as the Wet-Normal Recovery point in this study. Those transient patterns under wet road conditions were sustained for a significant amount of time. After that, traffic flow patterns finally returned to the dry-normal fundamental relationship as the road conditions eventually became dry.

In this section, the entire recovery stages, i.e., from the road condition recovery point to the normal pattern recovery point will be analyzed. Based on the studies, two types of recovery patterns were identified with different levels of traffic volume.

Type 1 Recovery Pattern: SFD pattern recovers to the free flow regime

The Type 1 Recovery Pattern was characterized by the traffic flow patterns where traffic flow recovered to the free-flow regime. As shown in Figure 33, the SFD pattern started to recover the wet-normal free-flow pattern sustained for a while, which was lower than the pre-snow free-flow level. With time, the speed improved to attain dry-normal speeds. These types of cases were observed when traffic was not congested during recovery to allow speed to increase by the free-flow speed.

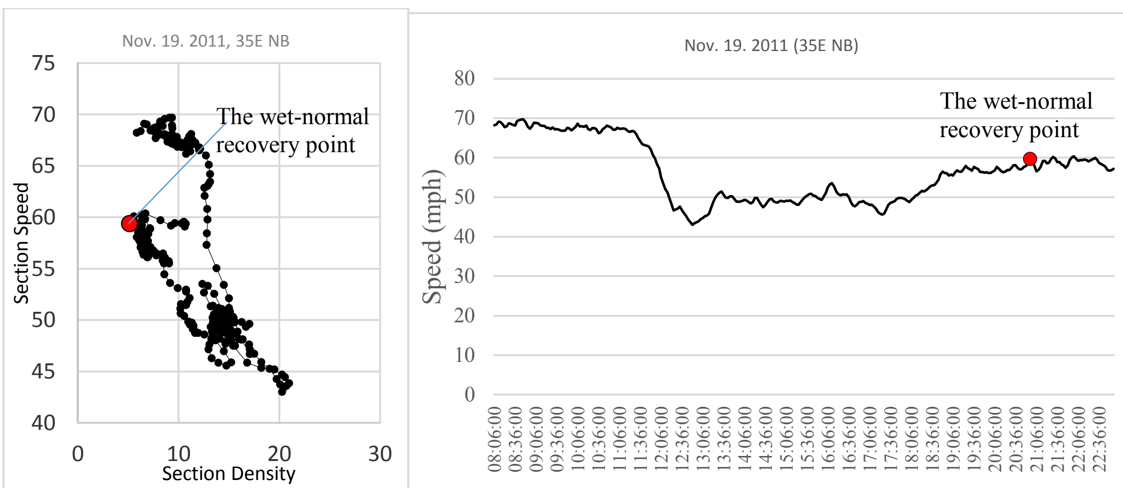

Figure 33: The wet normal recovery point in the SFD and speed variations when traffic flow recovered to the free-flow regime

Type 2 Recovery Pattern: SFD pattern recovers to the congested regime

The Type 2 Recovery Pattern was characterized by the traffic flow patterns where the SFD pattern started to show a consistent pattern of fundamental relationships in the congested regime. As shown in the speed variations plot in Figure 34, speed started to decrease approximately at 15:20 because of traffic congestion before reaching a free-flow speed. However, in the SFD, the pattern started to converge onto the fundamental relationship at the red point. The speed level was lower than the dry-normal level because of wet road conditions. The fundamental relationship pattern was maintained for a while before transferring to the dry-normal fundamental relationship when the road became dry. Figure 35 shows examples of such types of recovery patterns during times of traffic congestion.

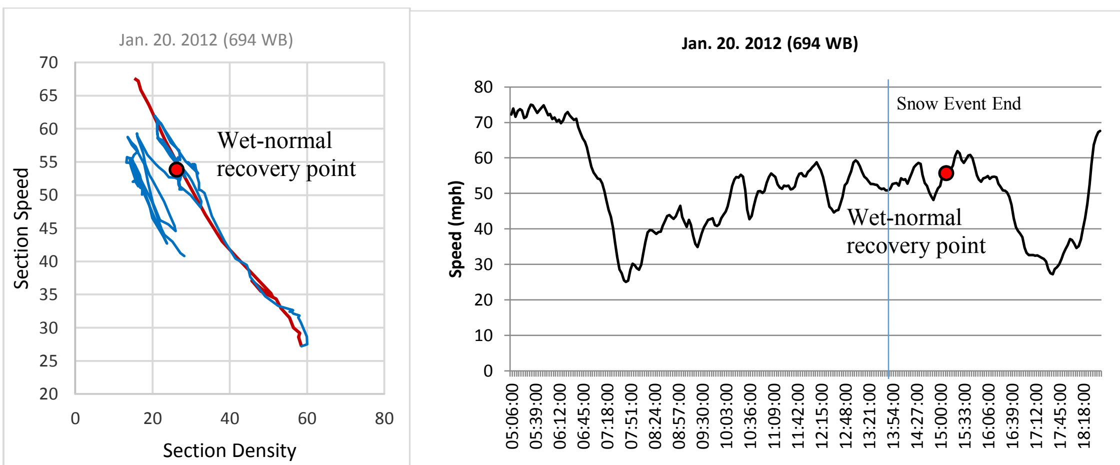

Figure 34: The wet-normal recovery point in the SFD and speed variations when traffic flow recovered to the congested regime

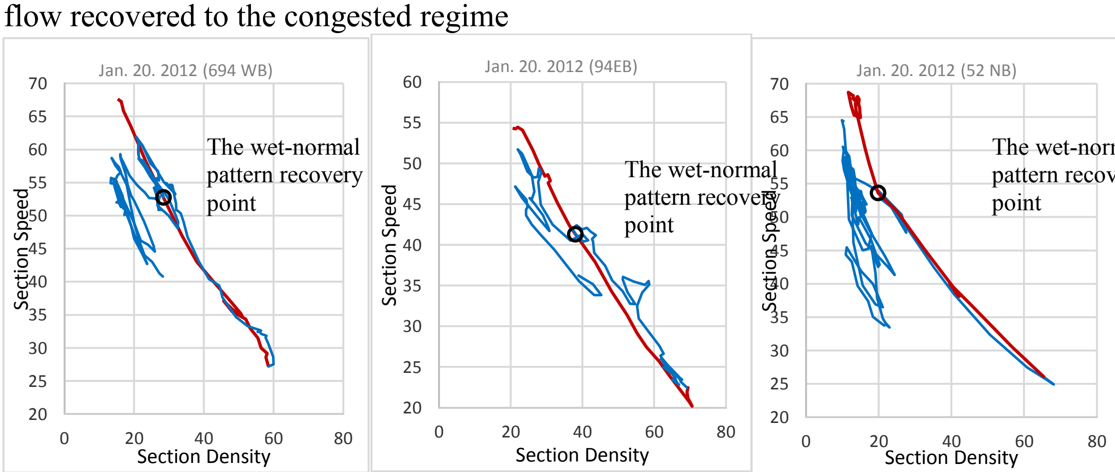

Figure 35: Typical patterns of the Type 2 Recovery Pattern

Based on the analysis, two different types of recovery patterns were identified with the factor of traffic volumes.

- Type 1 Recovery Pattern – Recovery to the free-flow regime: Under low traffic volumes
- Type 2 Recovery Pattern – Recovery to the congested regime: Under significant traffic volumes

As illustrated in Figure 36 (A), the speed increasing pattern of SFD started to sustain the speed level when wet-normal conditions were recovered. Note that the speed level is lower than the dry-normal level. In the case of (B), the speed increasing pattern began to decrease as traffic congestion starts. However, the SFD pattern converges into the fundamental relationship when wet-normal condition is attained. In a similar way, the fundamental relationship curve is located below the dry-normal relationship curve.

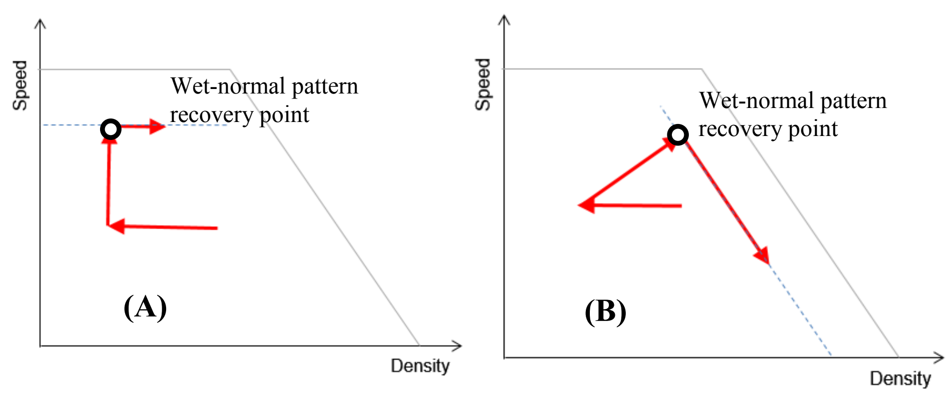

Figure 36: Schematic Diagrams of Recovery Pattern Types: Type 1 (Left); Type 2 (Right)

4.3. Identification of Phase Change Points of Traffic Flow Process

Based on the general traffic flow process during snow events, the seven phase change point were identified within the speed variations and speed-density fundamental diagrams. A set of phase change point includes: SRST (Speed Reduction Starting Time), LST (Lowest Speed Time), RST (Recovery Starting Time), RCR (Road Condition Recovery time), PSR (Posted Speed limit Recovery time), WNR (Wet Normal Recovery time), and NPR (Normal Pattern Recovery time).

4.3.1. Definitions of Phase Change Points

- SRST (Speed Recovery Starting Time): The starting point where the speed variations starts to depart the average normal speed level at least for an hour due to the snow precipitation.
- LST (Lowest Speed Time): The minimum speed point during the snow event.
- RST (Recovery Starting Time): The starting point where the speed variations starts recover to increase continuously to reach or exceed the level of posted speed limit.
- RCR (Road Condition Recovery time): The point when the road condition within the snow corridor recovers the bare lane condition after the recent snow plowing operations, which allows traffic speed to increase smoothly to reach the posted speed limit of the given snow section.
- PSR (Posted Speed limit Recovery time): The point when the speed achieves the posted speed limit of the given snow section.

- WNR (Wet Normal Recovery time): The point where traffic flow recovers the sustainable status under the wet pavement condition while the traffic flow pattern behaves in an expected way based on the fundamental relationships
- NPR (Normal Pattern Recovery time): The point where speed variation recovers the average dry normal level within the adjustable ranges which can be regarded acceptable as normal. Those adjustable ranges are determined within 0-20% of the average dry normal level depending on the needs of interest.

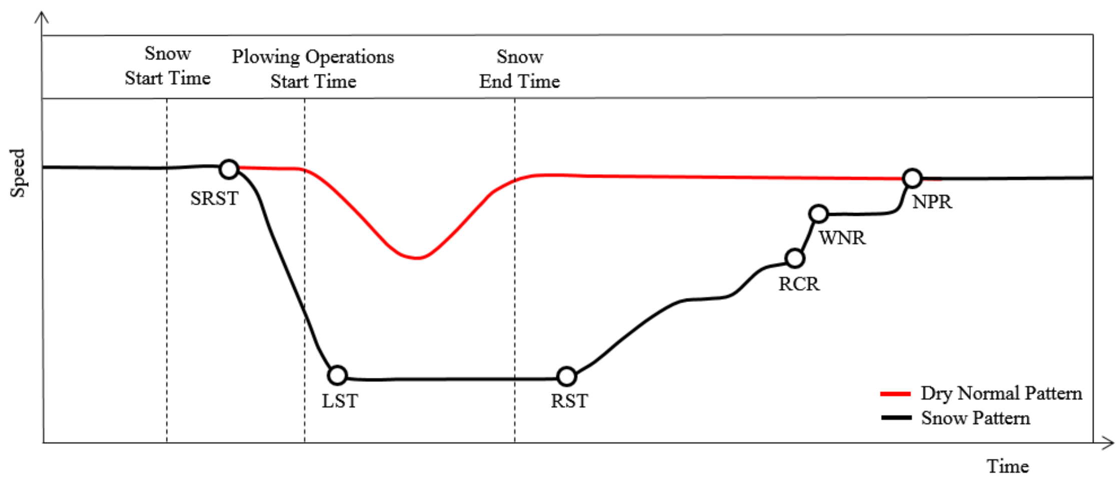

Figure 37: Phase change points and the snow event information in the snow-affected speed variations

4.3.2. Characteristics of Phase Change Points

- SRST (Speed Recovery Starting Time)

  SRST indicates the time where the traffic flow starts to decline because of the snow precipitation. SRST was identified by comparing with the dry-normal speed patterns by finding the point where speed departed the dry normal pattern.

- LST (Lowest Speed Time)

  LST indicates the time where the speed attains the minimum level during snow events. The factors determines the LST include both precipitation intensity and traffic volumes.

- RST (Recovery Starting Time)

  RST indicates the time where the speed starts the continuous recovery to reach the posted speed limit. Snow precipitation shows irregular variations and/or recurs before the road is completely recovered. Due to this nature, the speed variations during snow events repeats multiple cycles where speed experiences reductions and recoveries. Among the multiple fluctuations of speed variations, RST is defined by the recovery starting point in the last cycle before reaching the posted speed limit.

  In Figure 38, the speed variations involved two cycles due to the changeable snow precipitations. For both cycles, speed recovery starting points were able to be found at (A) and (B), but the last point was determined as RST as it leaded to the posted speed limit after the continuous recovery.

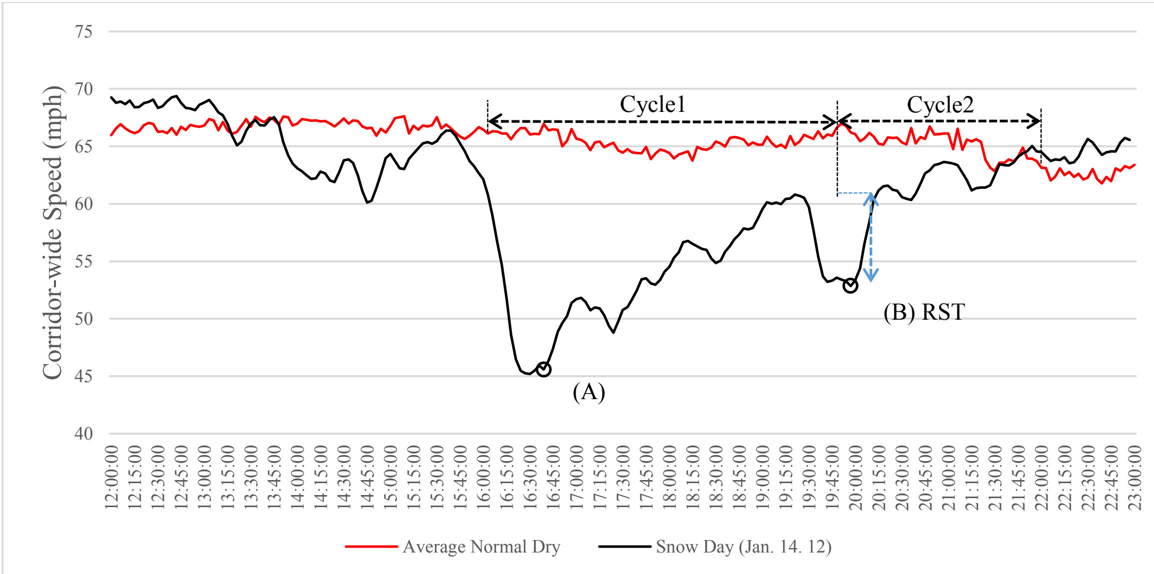

Figure 38: Determining RST Point in the Traffic Flow Variations of 94 WB Snow Corridor during snow events in January 14, 2012

- RCR (Road Condition Recovery Time)

  RCR indicates the time where the traffic flow starts to improve substantially at the immediate snow plowing operation under the bare lane condition. The times of snow plowing operations are represented by the three types of disturbance patterns such as loop-disturbance pattern, density-disturbance pattern and the vertical-increasing pattern. Traffic volume variations are required to be examined if the disturbance was resulted by the short-time variability of traffic volumes. Among the patterns of snow plowing operations, the last point before reaching the posted speed limit was identified as RCR by reflecting the definition of the current operational measure, or the “bare lane regain time.”

- PSR (Posted Speed limit Recovery time)

PSR literally indicates the time where the traffic speed achieves the posted speed limit of the snow section. PSR has its importance in terms of traffic flow management and operations, as it indicates that the road facilities become to accommodate the traffic flow at the designed level of appropriateness.

- WNR (Wet Normal Recovery Time)

WNR indicates the time where the traffic flow is considered to behave in the expected way in terms of fundamental relationships of traffic flow when the wet road was recovered. If traffic is not congested during the road recovery, traffic pattern will return to the free-flow regime of fundamental relationship by exhibiting the sustaining speed for a while. If traffic is congested, traffic pattern will return to the congested regime of fundamental relationship by converging into the wet-normal UK curve. It should be noted that the speed levels at both cases are lower than the dry-normal level.

WNR meets the needs of traffic management sector by helping them to decide when they start traffic control strategies so that traffic flow respond to the control in an expected way.

The snow plowing operations still influence on WNR pattern because the additional plowing operations are continued to clear the snow mounted in the shoulders, but it is also significantly factored by the natural environments such as the heats from the sunlight and the frictional heat from the vehicles.

- NPR (Normal Pattern Recovery Time)

  NPR indicates the time where the traffic flow recovers the average dry normal level after the snow event ended. NPR was identified by finding the point where the snow-affected speed converge into the acceptable range of the dry-normal level. According to the needs of interests, the acceptable range can be adjusted within the 0-20% of the average dry-normal level.

CHAPTER 5: DEVELOPMENT OF AUTOMATIC PROCESS FOR ESTIMATING OPERATIONAL MEASURES

In the previous chapter, the phase change points including SRST, LST, RST, RCR, PSR, WNR and NPR were identified in both the speed variations and speed-density planes. Using those information denoting the recoveries of traffic flow and road surface conditions, the alternative traffic data-based operational measures for winter snow management will be established. Then a computer-based automatic process will be developed to estimate the operational measures. Chapter 5 consists of the following terms:

5.1 Development of Operational Measures for Winter Snow Management

5.2 Overview of the Automatic Process

5.3 Review of the Previous Studies and Enhancement on the Existing Process

5.4 Development of a Process for Identifying the Newly Identified Phase Change Points

5.5 Development of a Process for Estimating the Operational Measures

5.1. Development of Operational Measures

The information used in formulating the traffic data-based operational measures includes the date and time of snow events and the phase change points identified in the previous sections. The set of phase change points are SRST, LST, RST, RCR, PSR, WNR and NPR. Figure 39 shows the schematic diagram of such information within the speed variations plot.

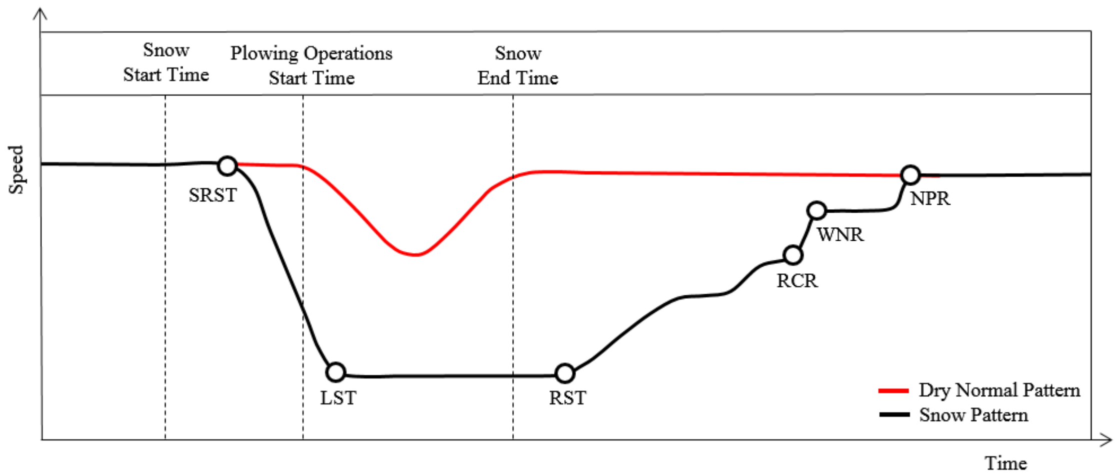

Figure 39: Phase change points and the snow event information in the snow-affected speed variations

By employing the above points, a set of alternative operational measures for winter snow management were developed as in below. The operational measures were mainly formulated by obtaining the time durations between the two selected phase change points. Providing diverse options of combination allows users to be selectively informed of the different features in the road condition recovery process. Also such different types permit in-depth implications on the winter snow managements by time. In addition, an operational measure estimating the amount of the maximum speed reduction during snow events was developed. At last, the ratio of snow-affected time duration to the entire snow event was approximated to develop an operational measure. The list of alternative operational measures developed is provided in the followings. The detail descriptions will follows.

- Snow event start time – SRST
- Snow event start time – LST
- Snow event start time – RST
- Snow event start time – PSR
- Snow event start time – RCR
- Snow event start time – WNR
- Snow event start time – NPR
- SRST – LST
- SRST – RST
- SRST – PSR
- SRST – RCR
- SRST – WNR
- SRST – NPR
- LST – RST
- LST – PSR
- LST – RCR
- LST – WNR
- LST – NPR
- RST – RCR
- RST – WNR
- RST – NPR
- Snow event end time – RCR
- Snow event end time – WNR
- Snow event end time – NPR
- RCR – WNR
- RCR – NPR
- WNR – NPR
- $U_{dry}(LST) - U_{snow}(LST)$
- Ratio of time duration where speed is less than the accepted level of dry-normal speed out of the entire snow event duration

As aforementioned, most of the operational measures were developed by calculating the time differences between the two points selected from the given dataset including the time of snow events and phase change points. Figure 40-Figure 41 below provide the example cases of such type of operational measures. Figure 40 illustrates the operational measures of ‘SRST-RST’, ‘SRST-RCR’, ‘SRST-WNR’, and ‘SRST-NPR’, and Figure 41 illustrate the operational measures of ‘snow event end time-RCR’, ‘snow event end time-WNR’, and ‘snow event end time-NPR.’

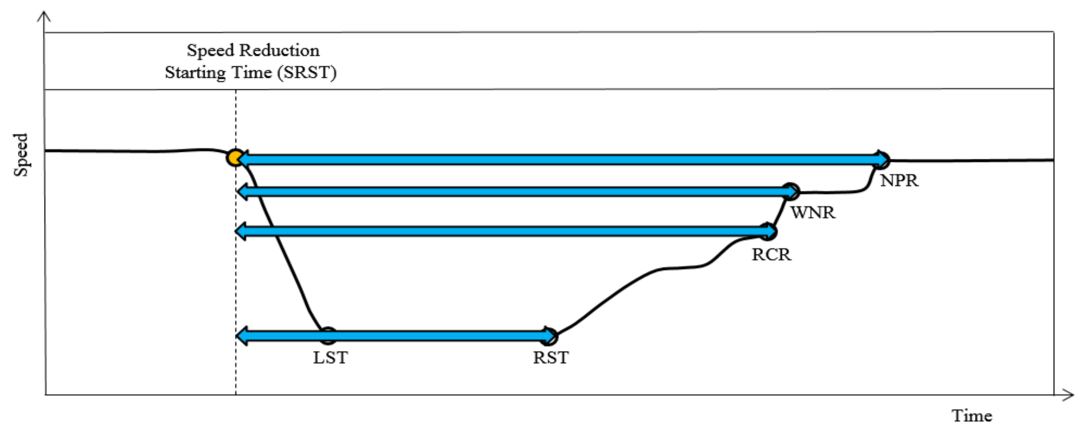

Figure 40: Operational measures of time durations from SRST to the four different phase change points

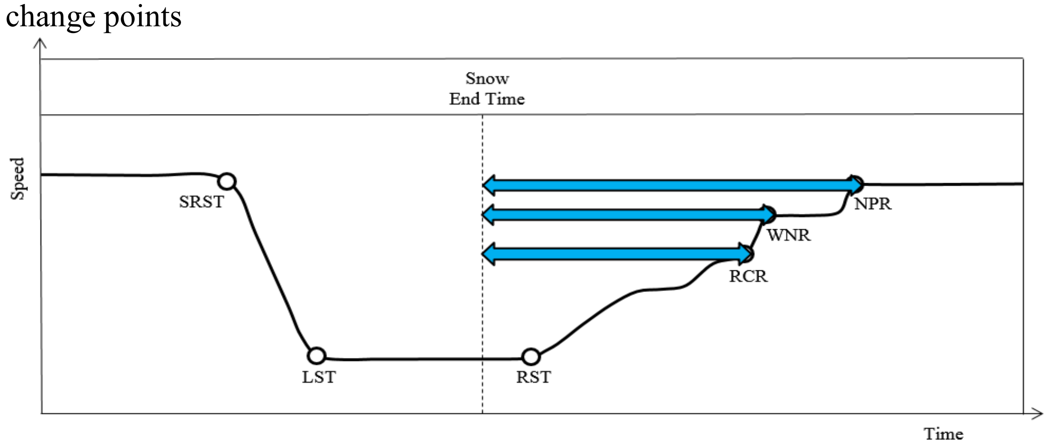

Figure 41: Operational measures of time durations from the snow event end time to the three different phase change points

Another type of operational measure is the maximum speed reduction during snow events. As illustrated in Figure 42, such measure was estimated by calculating the difference between the speeds at LST during snow events compared to the dry-normal level. It should be noted that the dry normal speed is developed by taking an average of the speed patterns of dry normal days within the same month with the selected snow event.

The amount of speed reduction at LST indicates the impact of snow precipitation on the traffic flow during snow events. Effectively conducted snow plowing operations in the initial stage would mitigate the speed reduction at LST.

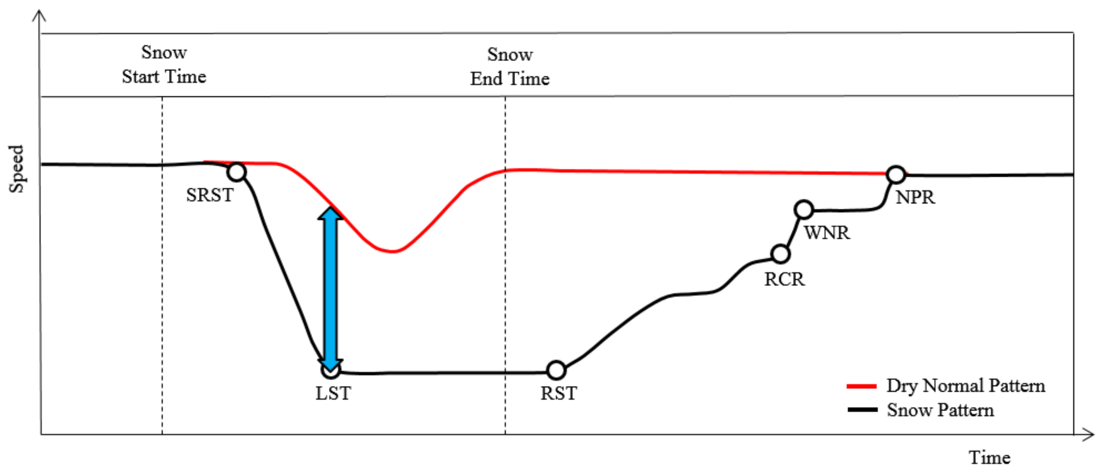

Figure 42: Operational measure of speed difference at LST compared to the dry-normal speed

Another type of operational measure is the ratio of snow-affected duration to the snow event duration which is well represented in Figure 43 below. In this study, the "snow-affected duration" is defined as the time where traffic speed remains less than the "acceptable dry-normal speed level" above which the traffic flow is considered acceptable as showing consistent patterns of traffic flow even though the speed is lower than the normal level. The yellow arrow labeled (B) denotes the “snow-affected duration.” The acceptable dry-normal speed level is determined by the user, but it is expected to be lied within 0-20% of the dry-normal speed level.

Having the snow event duration as the blue arrow labeled (A) in the figure, the ratio of the snow affected duration to the snow event can be calculated as $\frac{(B)}{(A)}$.

Smaller the measure is, the better the snow plowing operations performed as it indicates the smaller portion of the weather-affected time compared to the entire snow event duration through the entire snow event.

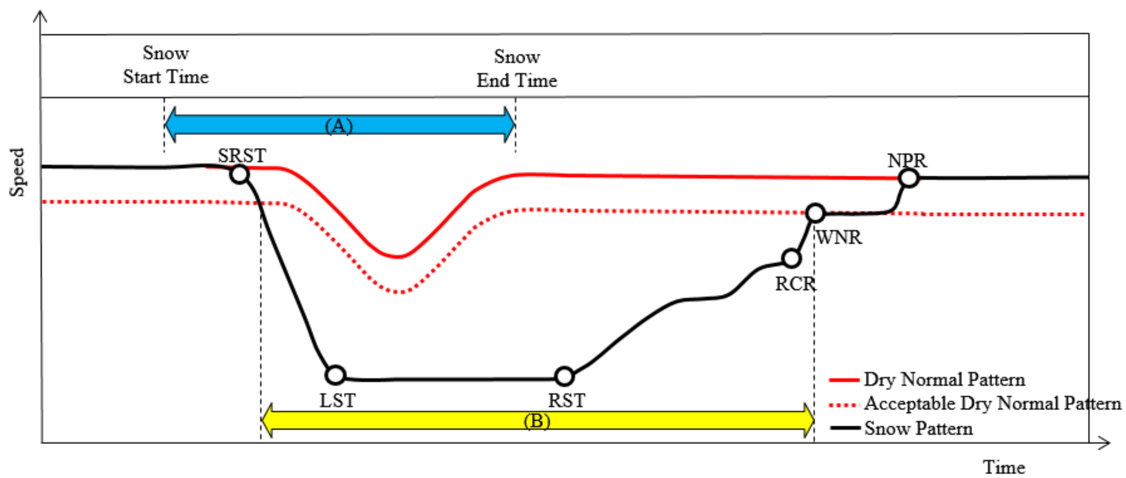

Figure 43: Operational measure of ratio of snow-affected duration to the snow event duration

5.2. Overview of the Automatic Process

In this section, the overall framework of algorithm to estimate the traffic data-based operational measures will be introduced. As provided in Figure 44, the input for the algorithm includes the snow event start/end time and date. Such input is used in determining the time range of traffic flow dataset which will be downloaded from the server of Transportation Management Center. The output for the algorithm is the set of user-defined operational measures for winter snow management.

The overall framework of algorithm consists of the three subordinate process, such as "Data extraction and processing", "Identification of phase change points", and "Estimation of operational measures for winter snow management." Figure 45-Figure 47 show the process of each subordinate process.

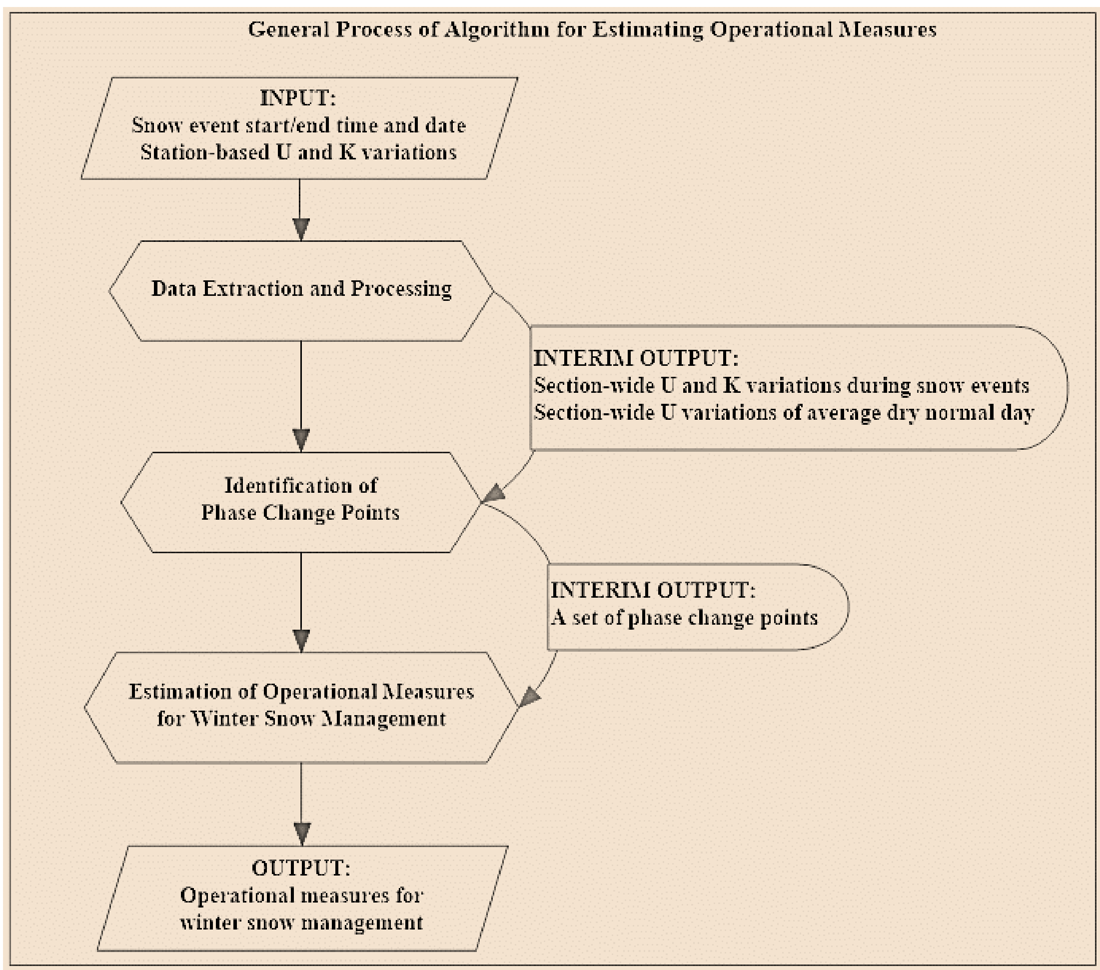

Figure 44: General Process of an Algorithm for Estimating the Operational Measures

Figure 45 below represents the process of “Data Extraction and Processing.” First, the traffic speed patterns of average dry-normal days are developed by selecting the dry-normal days based on the weather information within the same month including the given snow event. Then, speed and density variations during snow events are also extracted based on the given information of snow events. Those dataset of station-based variations is then processed to develop the section-wide variations, such as the section-wide speed, section-wide density and traffic volume variations within snow section.

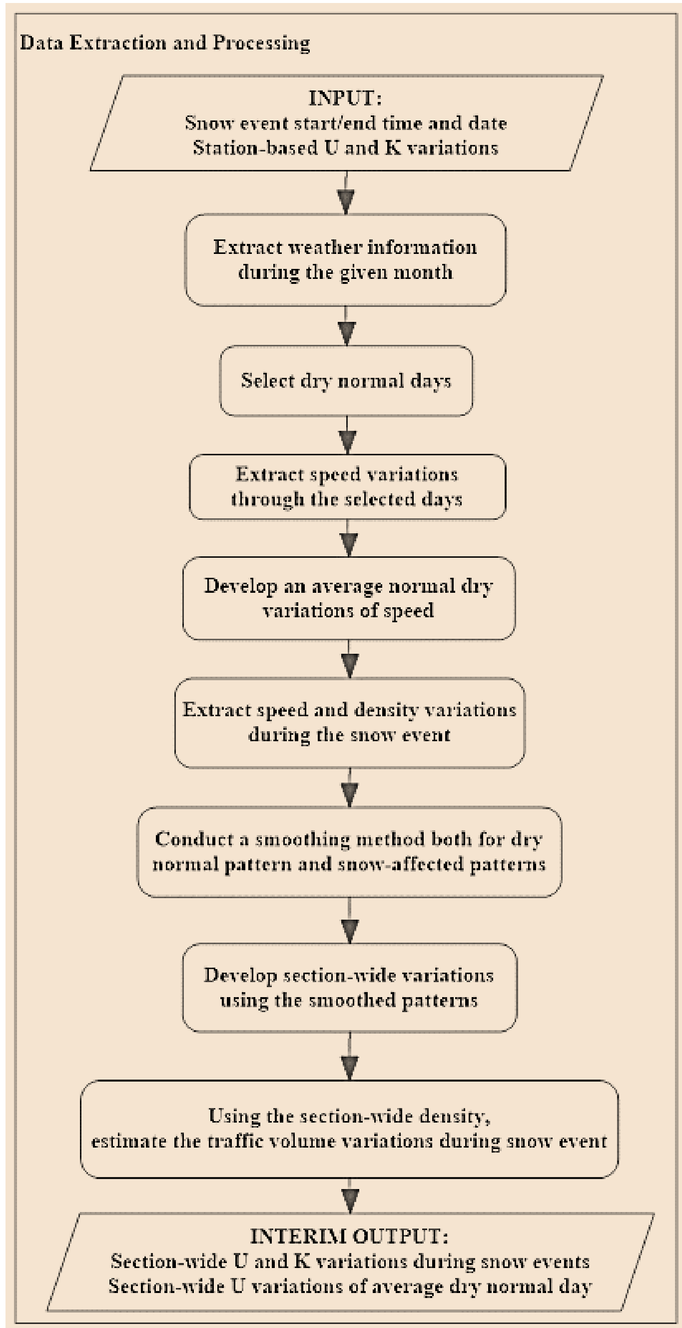

Figure 45: Subordinate Process of Data Extraction and Processing

As shown in Figure 46, the interim output of section-wide traffic flow variations both during snow events and dry-normal days are inserted as input in the process of "Identification of the phase change points." The phase change points are identified in the order of SRST (Speed Reduction Starting Time), NPR (Normal Pattern Recovery), LST (Lowest Speed Time), RST (Recovery Starting Time), PSR (Posted Speed limit Recovery), WNR (Wet-Normal pattern Recovery), and RCR (Road Condition Recovery) at last.

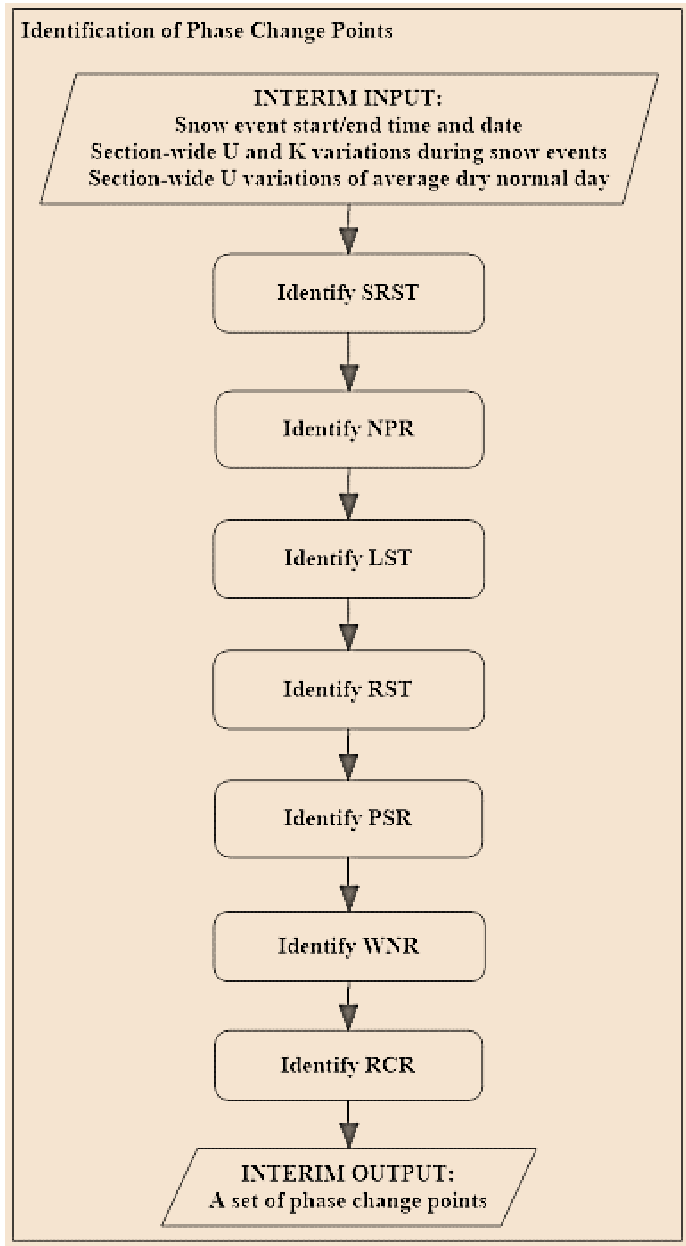

Figure 46: Subordinate Process of Identification of Phase Change Points

As appeared in Figure 47, the resulted phase change points are then employed in estimating the operational measures based on the simple steps. The operational measures as an output for the algorithm include the time durations between two phase change points of interests, the maximum speed reduction at LST, and the ratio of snow-affected time to the snow event duration. The detail step-by-step will be described in the following sections.

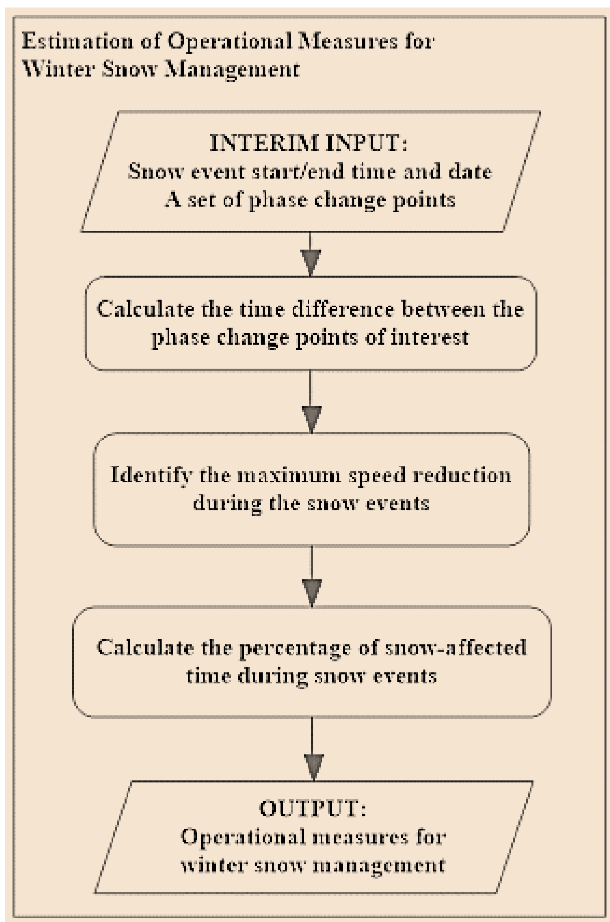

Figure 47: Subordinate Process of Estimation of Operational Measures

5.3. Review of the Previous Studies and Enhancement on the Existing Process

5.3.1. Review of the Previous Studies

The previous studies conducted by Kwon [2] have featured the four phase change points in the speed variations during snow events, including SRST (Speed Reduction Starting Time), LST (Lowest Speed Time), RST (Recovery Starting Time) and SRT (Speed Recovery Time). In this section, the automatic process for identifying those phase change points will be briefly reviewed. The general information of the algorithm is as following:

- Input: Snow event start and end time and the speed variations during snow events
- Output: The four phase change points

It should be noted that the algorithm used both smoothed and quantized speed data in determining the phase change points.

SRST (Speed Reduction Starting Time)

Step i) Find the first point of speed reduction in a quantized speed graph.

Step ii) Refine the point by searching back for the highest speed on the smoothed speed graph as illustrated in Figure 48 below.

LST (Lowest Speed Time)

Step i) Identify the last point of the speed reduction in a quantized speed graph as in Figure 48 below.

RST (Recovery Starting Time)

Step i) Find the point after which the speed continuously increases.

Step ii) Refine the point by searching back for the lowest speed on the smoothed speed graph as illustrated in Figure 48 below.

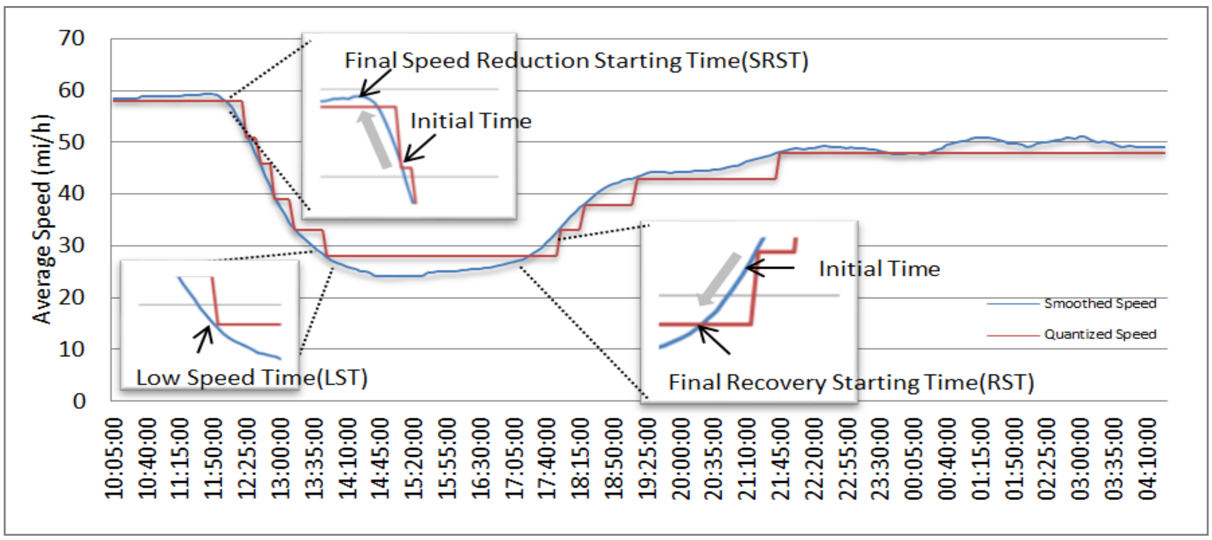

Figure 48: Identification of Phase Change Points of the Existing Algorithm [2]

SRT (Speed Recovery Time)

Step i) Identify the time whose smoothed speed becomes greater than the pre-determined threshold level, i.e., 85% of the pre-snow level, for an hour. If any point is identified, determine the point as SRT.

Step ii) If it is not found any point satisfying the condition in Step (i), search the smoothed speed variations if the speed decreases shortly after.

Step iii) If it is found any point satisfying the condition in Step (ii), examine the corresponding density variations if it increases.

Step iv) If it is found any point satisfying the condition in Step (iii), identify the first point which after the speed decreases as SRT.

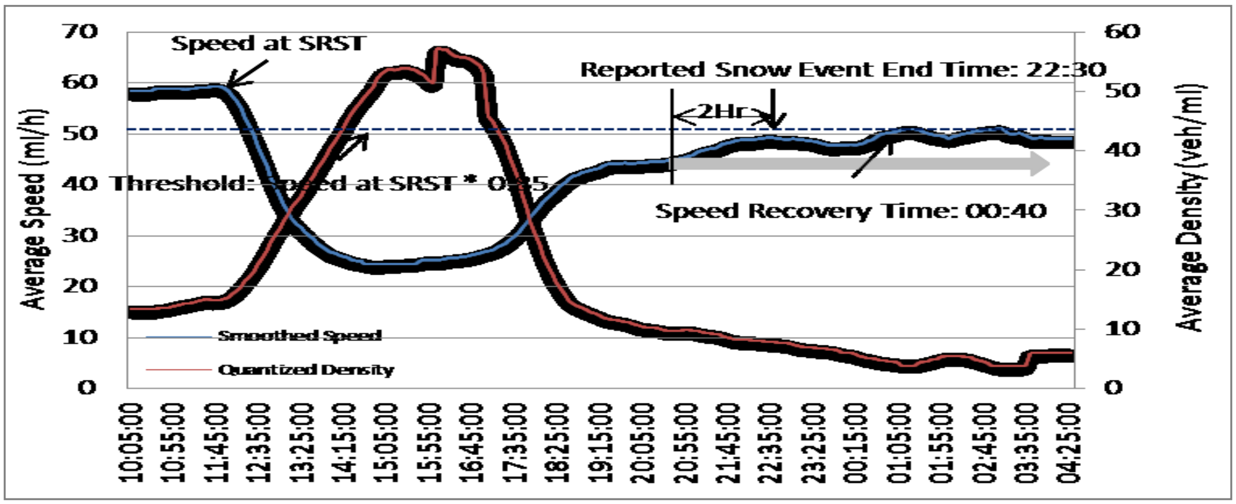

Figure 49: Identification of Speed Recovery Point [2]

5.3.2. Enhancement on the Existing Process

As mentioned earlier, the general framework of the algorithm to identify some phase change points, such as SRST and RST, were adopted with some enhancements from the earlier algorithm developed by Kwon [2]. Also, another type of phase change points, such as PSR and NPR were newly added by enhancing in defining phases in the speed variations during snow events. The enhancement efforts on the existing algorithm will be described in this section. It will be introduced in the order of the process of algorithm, i.e., SRST, NPR, RST, and PSR. It should be mentioned that LST remained same with the previous algorithm.

SRST (Speed Reduction Starting Time)

The algorithm to find SRST was enhanced by employing the dry normal speed variations to compare with the snow-affected patterns, while the existing pattern only examine the snow-affected pattern itself. The enhancement allows to distinguish the normal traffic variations due to the traffic congestion from the speed reduction resulted by the snow precipitations. The step-by-step is as followings:

Step i) Retrieve the smoothed speed variations both of snow event and dry-normal day.

Step ii) Starting from the snow event start time to the snow event end time plus 8hrs, find the point where the snow-affected speed deviates the dry-normal speed for n time intervals (n = 20), i.e., the first point which after Equation 14 remain true to determine it as SRST.

$$U_{dry} - U_{snow} > 0$$

Equation 14

Step iii) If none of points were found satisfying Equation 14, find the first point of speed reduction in the quantized speed variations.

Step iv) Refine the point by searching back the smoothed speed to find the first point to start speed reduction.

NPR (Normal Pattern Recovery Time)

For the similar reasons with SRST, the process to identify NPR employs the corresponding dry-normal speed variations in identifying NPR. The step-by-step to identify NPR is as following:

Step i) Retrieve the smoothed speed variations both of snow event and dry-normal day.

Step ii) Starting from SRST to the end of data (8 hours after the snow event end time), find the point where the snow-affected speed returns to the dry-normal speed even one time interval, i.e., the point where Equation 15 satisfies.

$$U_{dry} - U_{snow} = 0$$

Equation 15

The overall process to define NPR was presented in the flow chart in Figure 50 below.

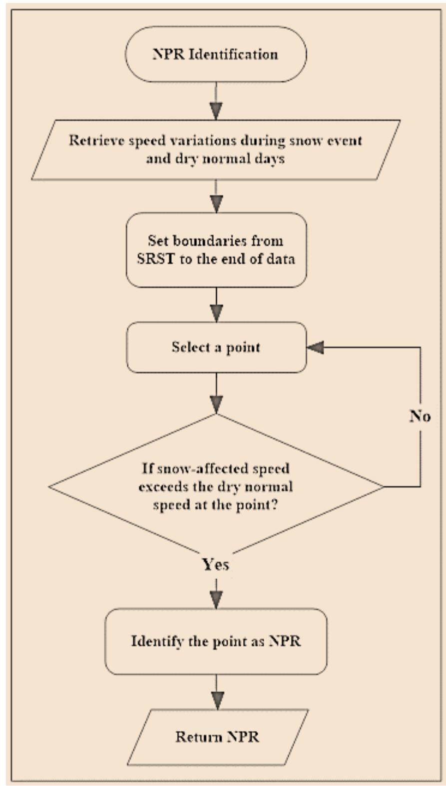

Figure 50: Flow Chart of Identification of NPR

RST (Recovery Starting Time)

RST is defined as the point which after the speed starts to increase continuously until reaching NPR. The previous algorithm locate the RST at the point where the lowest speed starts to increase significantly. The enhanced algorithm assumed that the speed variations can experience the significant speed reduction due to the recurring snow precipitations. In such cases, RST does not necessarily found near the LST, but more reasonable to identify it at the lastly located starting point of speed increase.

The automatic process to identify RST was designed to find the lastly located significant speed reduction before the dry-normal speed is recovered. The detail step-by-step is as followings:

Step i) To determine the range of RST, examine if the traffic is congested during road recovery period using Equation 16.

$$U_{snow}(SRST) - U_{snow}(t) \geq \alpha\ mph\ (where\ \alpha = 30)$$

Equation 16

Step ii) If traffic is uncongested, the boundary of RST is determined as from LST to NPR. If traffic is congested, the boundary of RST is determined as from LST to the congestion starting time.

Step iii) Starting from LST, identify if speed turns to decrease in the quantized speed variations using Equation 17.

$$U_{quant}(t-1) - U_{quant}(t) \leq 0$$

Equation 17

Step iv) If speed reduction is identified in Step (iii), determine if speed reduction amount is significant in the smoothed speed variations. If the speed reduction amount is greater than the pre-determined threshold, define the lowest speed point as RST which after the speed continue to increase to NPR.

Step v) If none of significant speed reduction is found within the boundary of RST, define LST as RST.

The process for identifying the congestion starting point is as follows:

Step i) Identify if traffic is congested by determining if speed was reduced up to $\boldsymbol{\alpha}$ mph ($\boldsymbol{\alpha}=30$) after snow event ended.

Step ii) If traffic is assumed congested, find the minimum speed point after snow event ended.

Step iii) Starting from the minimum speed point, search back the speed variations to find the starting point where after speed continuously decreases to define it as "Congestion Starting Point."

The overall process of identification of RST was presented in the flow chart in Figure 51.

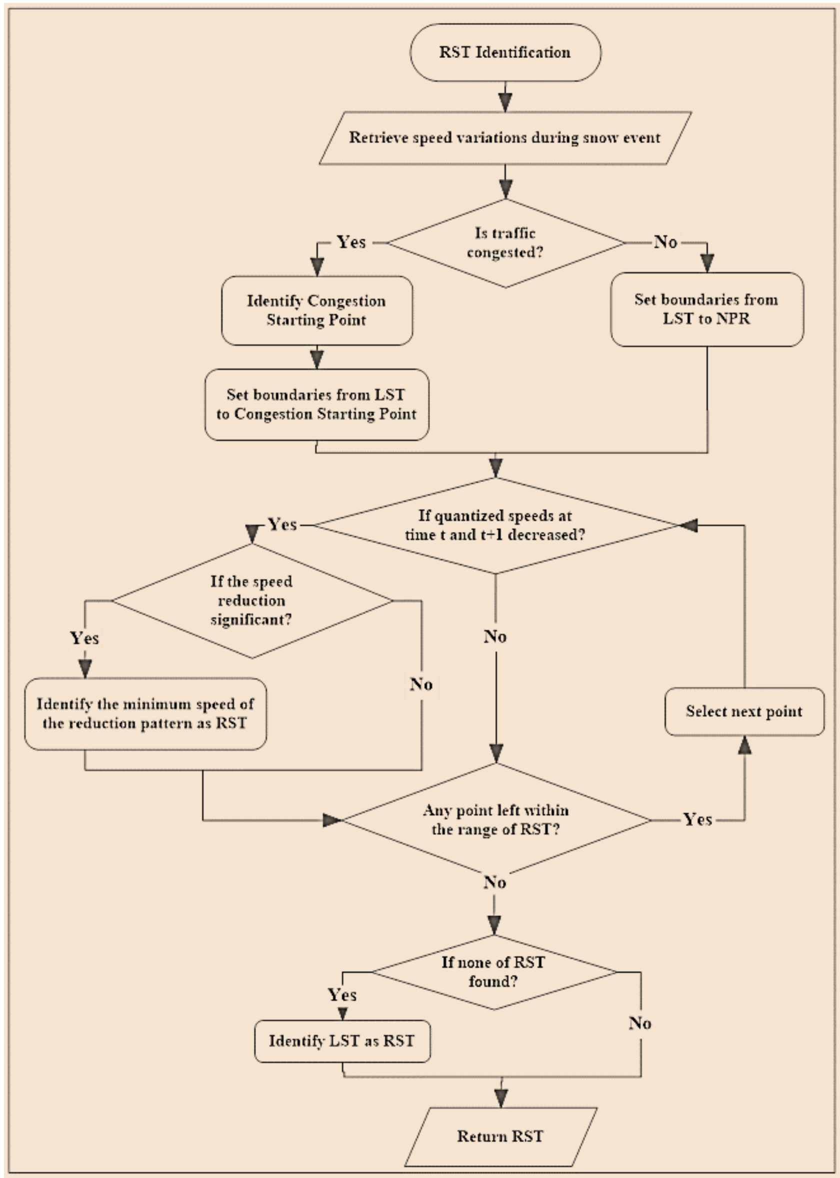

Figure 51: Flow Chart of Identification of RST

PSR (Posted Speed Limit Recovery Time)

PSR defines the point where the speed reaches the posted speed limit of the current snow section. PST was newly identified in this study with the need to locate the point where the traffic flow recovers the minimum level of stability, which the traffic system operators are interested in. The automatic algorithm is as following:

Step i) Starting from RST to the end of traffic data, find the point where the speed reaches the level of Posted speed limit – α mph (α=3) to identify it as PSR. The threshold of α was given to allow flexibility in determining the desired time.

5.4. Development of a Process for Identifying the Newly Identified Phase Change Points

In this section, it will be described the algorithm of the newly developed phase change points, i.e., WNR and RCR. The detail process will be described in the followings.

5.4.1. Identification of WNR

WNR was defined as the point which after the "wet-normal fundamental relationship curve" starts in the speed-density plane. It was defined the "wet-normal fundamental relationship curve" was created by the series of points which show consistent relationship corresponding to the fundamental diagram of traffic flow, even though the speed level was 0-20% less than the speed level of dry-normal days due to the wet road conditions. Having known that the UK fundamental diagrams consists of the two different regimes, i.e., the free-flow regime and the congested regime, it will be applied different algorithm depending on whether the traffic is congested during the road recovery. If it was identified uncongested, the starting point to maintain the constant speed level above the posted speed limit will be identified as WNR. While, if it was identified congested, the starting point to converge into the "wet-normal fundamental relationship curve" will be identified as WNR.

The automatic process of Identification of WNR comprises of the following process:

Step 1: Determination of Range of WNR

Step 2: Identification of WNR

The overall process of identification of WNR is presented in the flow chart as in Figure 52.

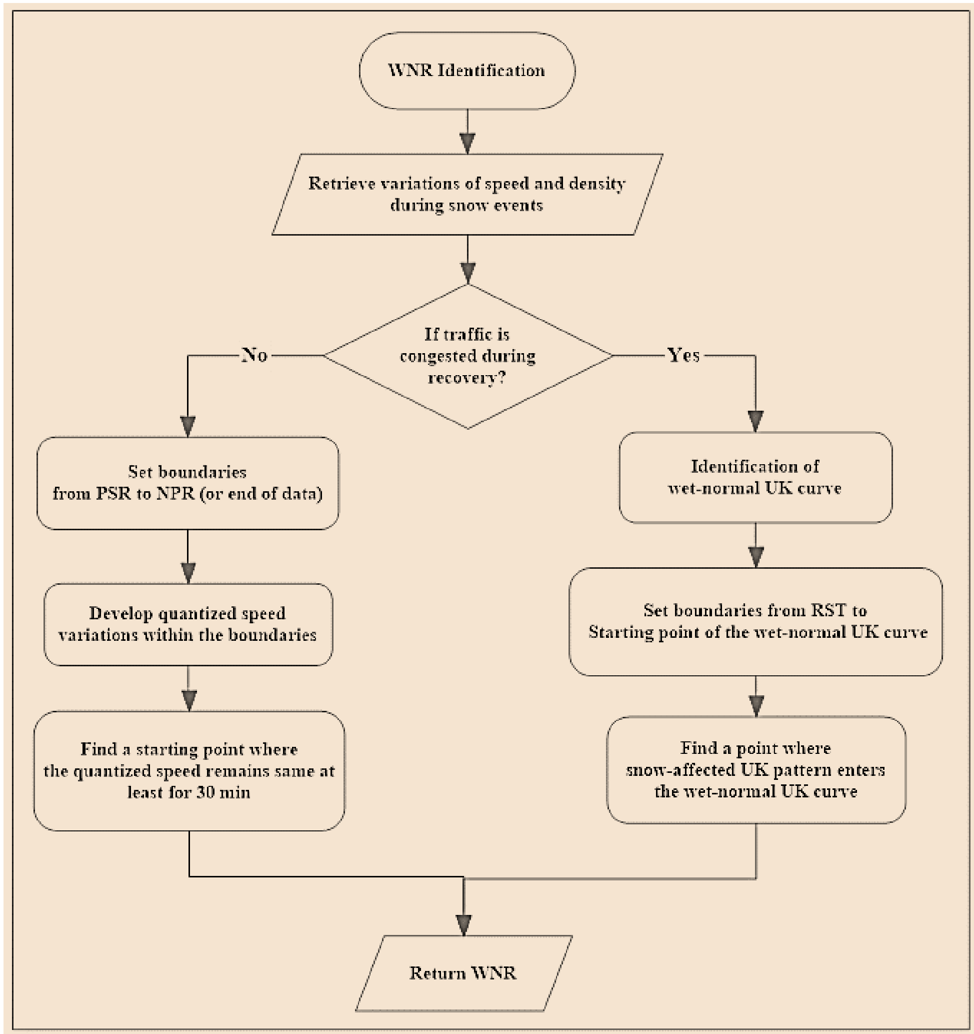

Figure 52: Flow Chart of Algorithm to Identify WNR

Step 1: Determination of Range of WNR

The range of WNR is determined depending on whether the traffic is congested during the road recovery. If traffic is congested, the boundary for WNR is from RST to the "Starting point of wet-normal UK curve." If traffic is not congested, the boundary for WNR is from RST to NPR, or end of data as necessary.

The step-by-step process for determination of range of WNR is as following:

Step i) Retrieve the speed variations during snow events

Step ii) To determine if traffic is congested during the road recovery period, search the speed variations from the point of snow event end time to apply Equation 18 below. If any point t exists satisfying Equation 18, meaning that speed reduction from the pre-snow incurred more than $\boldsymbol{\alpha}$ mph ($\boldsymbol{\alpha}$=30), it will be determined traffic is congested during the road recovery period. Otherwise, it will be determined traffic is uncongested during the road recovery period.

$$U_{snow}(SRST) - U_{snow}(t) \geq \alpha \text{ mph (where } \alpha = 30)$$

Equation 18

Step iii) If traffic is determined uncongested during road recovery period, the range of WNR is determined as from PSR to NPR. If NPR does not exists, the range of WNR is from PSR to the end of data extracted, 8 hours after the snow event end time.

Step iv) If traffic is determined congested during road recovery period, the range of WNR is determined as from RST to the starting point of the "wet-normal fundamental curve."

The process to determine the "wet-normal fundamental curve" is as following:

Step i) Retrieve the speed variations from the congestion starting point to the end of the traffic data.

Step ii) Within the boundary, find the minimum speed point to reserve the point as the starting point of the "wet-normal fundamental curve."

Step iii) Within the boundary from the minimum speed point to the end of data, find the maximum speed point to reserve the point as the end point of the "wet-normal fundamental curve."

Step iv) Return all series of points in between the start and end point of the "wet-normal fundamental curve."

The automatic process to determine the "wet-normal fundamental curve" is presented in the flow chart in Figure 53.

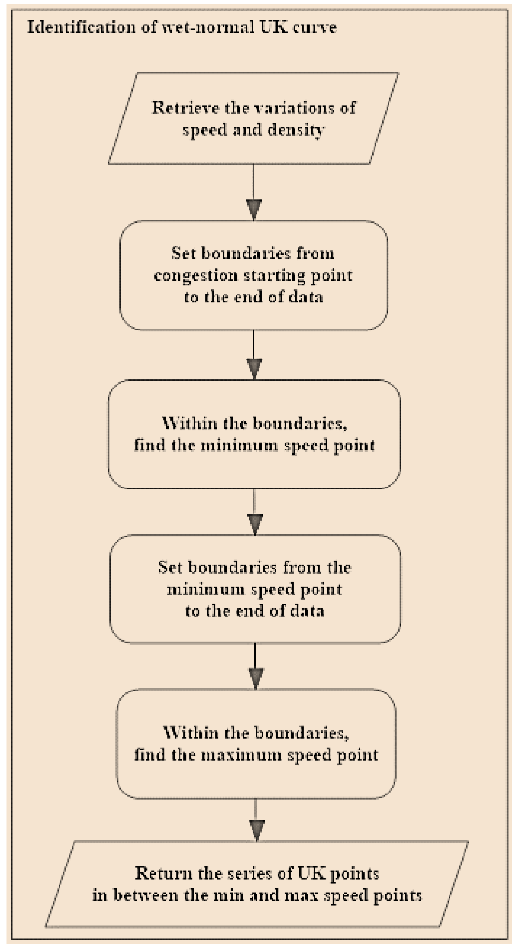

Figure 53: Flow Chart of Determination of Wet-Normal UK Curve

Step 2: Identification of WNR

The process to identify WNR is determined based on whether traffic is congested during the road recovery period.

If traffic is uncongested

In the free-flow conditions, WNR is identified at the point where the speed variations start to maintain a certain level above the posted speed limit for a while. The detail step-by-step is as following:

Step i) Develop the quantized speed variations

Step ii) Within the pre-determined boundaries of WNR, search the quantized speed variations to identify any point t satisfying Equation 19 to identify it as temporary WNR.

$$U_{quant}(t-1) - U_{quant}(t) = 0$$

Equation 19

Step iii) In the smoothed speed variations, identify the maximum speed point within the range of $\boldsymbol{\alpha}$ -time-intervals ($\boldsymbol{\alpha}$=3) before and after the temporary WNR to define it as final WNR.

If traffic is congested

In the congested conditions, WNR is defined at the point where the speed-density patterns converge into the estimated "wet-normal fundamental curve." In the automatic algorithm for identifying WNR, the point where the UK pattern first intersect the estimated "wet-normal fundamental curve" will be found to return it as WNR. The detail step-by-step is as followings:

Step i) Within the pre-determined boundaries of WNR, select two consecutive points for the reference points, i.e., $(K_1,\ U_1)$ and $(K_2,\ U_2)$ as shown in Figure 54 below.

Step ii) Develop a linear equation between K and U that passes through the selected reference points in the form of Equation 20.

$$a_1 U + b_1 K + c_1 = 0$$

Equation 20

where, $a_1 = \frac{(U_2 - U_1)}{(K_2 - K_1)}$, $b_1 = -1$, and $c_1 = -a_1 + K_1$

Step iii) Select another two consecutive points within the "wet-normal fundamental curve," i.e., (K_3, U_3) and (K_4, U_4) as shown in Figure 54.

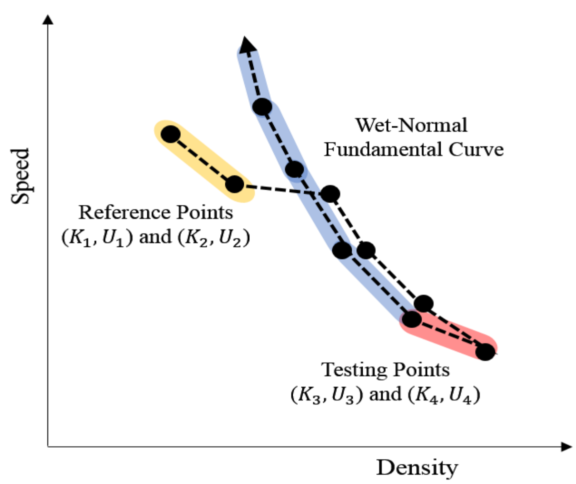

Figure 54: Selection of Reference Points and Testing Points in UK Diagram

Step iv) Test if the segment of the reference points and the segment of the testing points are intersected using Equation 21 and Equation 22:

$$(a_1 U_3 + b_1 K_3 + c_1) \cdot (a_1 U_4 + b_1 K_4 + c_1) < 0$$

Equation 21

$$U_3 \leq y \leq U_4$$

Equation 22

$$\text{where, } y = \left(\frac{c_2}{a_2} - \frac{c_1}{a_1}\right) / \left(\frac{b_1}{a_1} - \frac{b_2}{a_2}\right)$$

The discriminative equation in Equation 21 was adopted for examining if the two given points are located in the other side of a given line. In addition to this, Equation 22 will allow to examine if the two segments share its intersection point. Validity of both Equation 21 and Equation 22 denotes the two selected segments intersect each other in the speed-density plane.

Step v) If intersection point is identified, assign the second point of the current testing point as WNR.

Step vi) Continue to repeat the same process of Step (iii)-(v) by altering the testing points within the estimated "wet-normal fundamental curve" while keeping the consistent reference point as appeared in Figure 55.

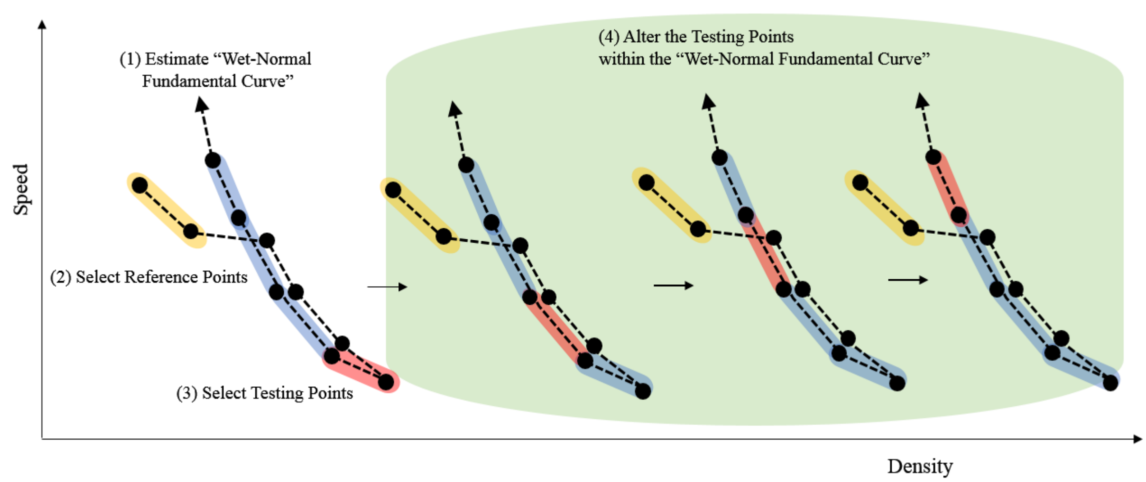

Figure 55: Alteration of Testing Points with Consistent Reference Points

Step vii) After finishing the iteration of testing points within the "wet-normal fundamental curve," select the new reference points next to the current pair to repeat Step (ii)-(vi) as shown in Figure 56.

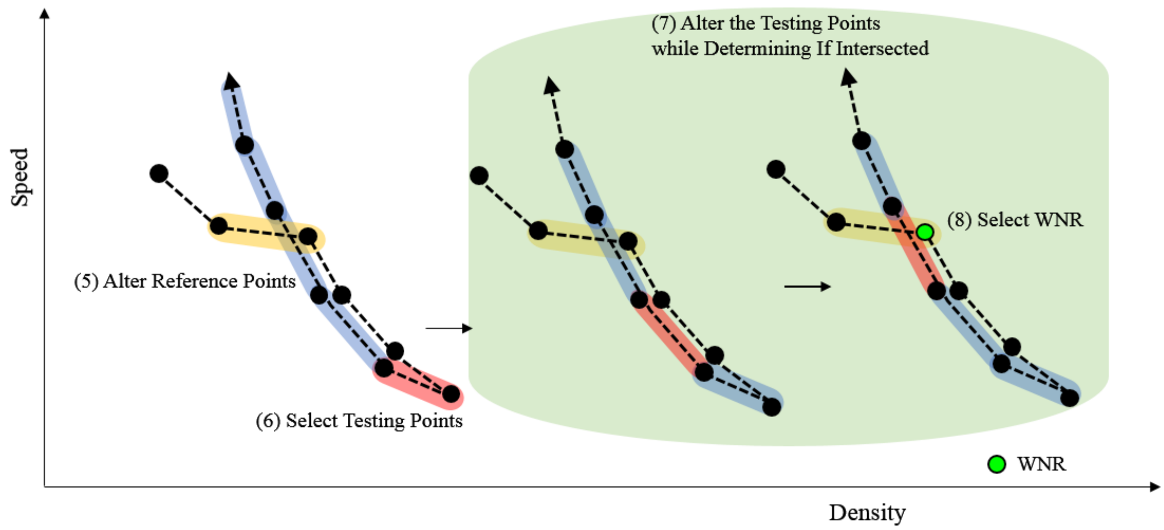

Figure 56: Alteration of Reference Points

Step viii) Continue Step (vii) within the boundaries of WNR.

The subordinate process of finding the point converging into the wet-normal fundamental curve, or WNR was presented in the flow chart in Figure 57.

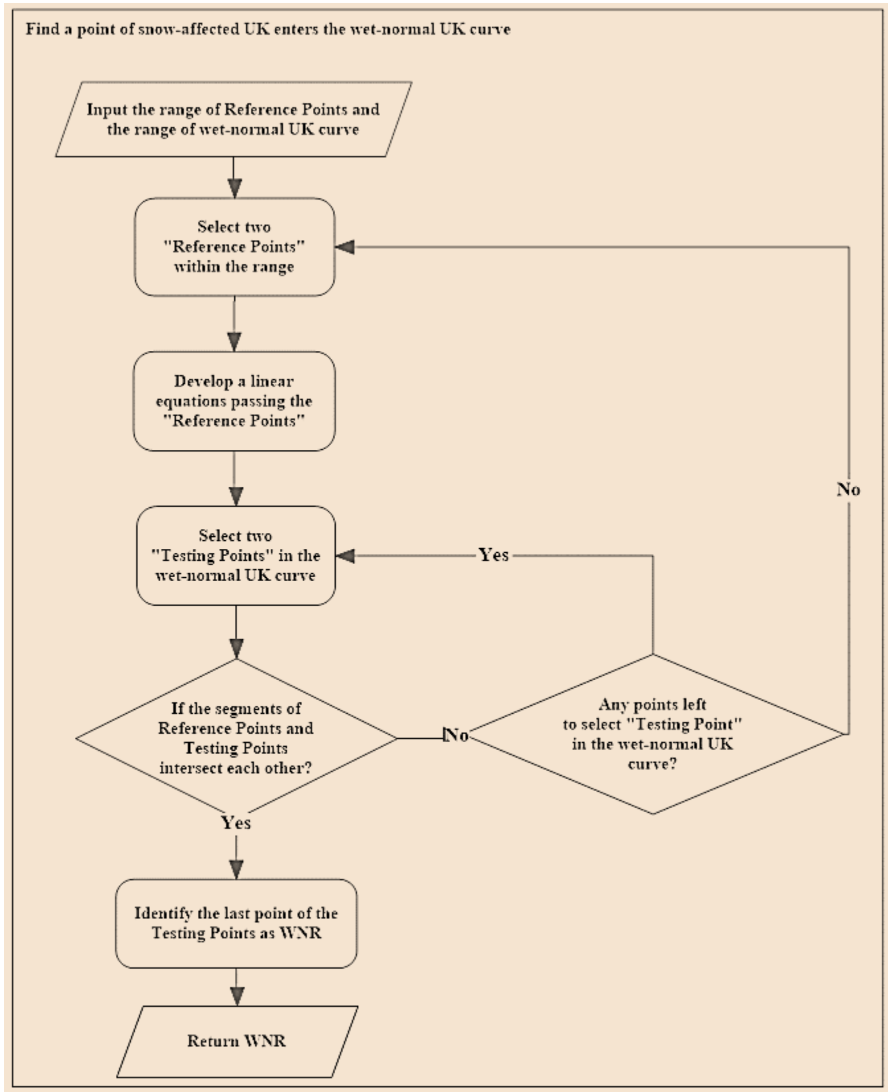

Figure 57: Flow Chart of Identification of WNR

5.4.2. Identification of RCR

Figure 58 below shows the general framework of identification of RCR. The variations of section-wide speed and section-wide density during snow event is used as an input and RCR point will be returned as an output. The process to identify RCR includes the five subordinate steps:

Step 1: Determination of range of RCR

Step 2: Identification of the loop-disturbance pattern

Step 3: Identification of the K-disturbance pattern

Step 4: Identification of the vertical-increasing pattern

Step 5: Identification of Snow Plowing Patterns

Step 6: Identification of RCR

The detail process for each subordinate step will be introduced in the following sections.

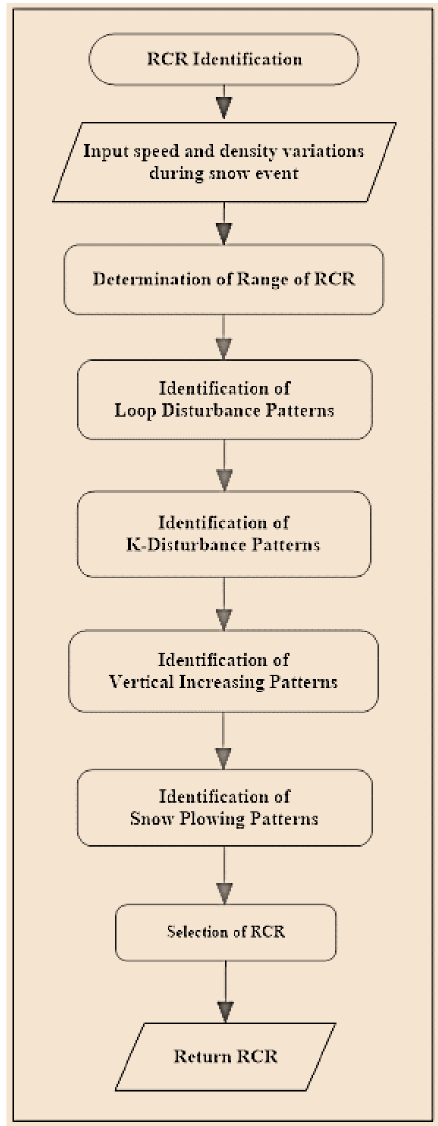

Figure 58: General Framework of Identification of RCR

Step1: Determination of Range of RCR

The range of RCR is determined depending on whether the traffic is congested during the road recovery. If traffic is congested, the boundary for RCR is from RST to the "Congestion starting point." It should be noted that the process to identify the "Congestion starting point" was previously mentioned in the process to identify RST. While, if traffic is not congested, the boundary for RCR is from RST to the first applicable point among WNR, NPR or the end point of the data. Most likely, RCR is expected to be found before the wet-normal pattern is recovered. However, WNR may not exist for some cases when traffic flow is recovered to its normal pattern immediately without showing transient pattern of WNR. Also, NPR may not observed within the extracted dataset if road condition is recovered in nighttime and that may cause the speed remaining less than the dry-normal level for unnecessarily long. For such cases, RCR will be searched within the range until the end of traffic data.

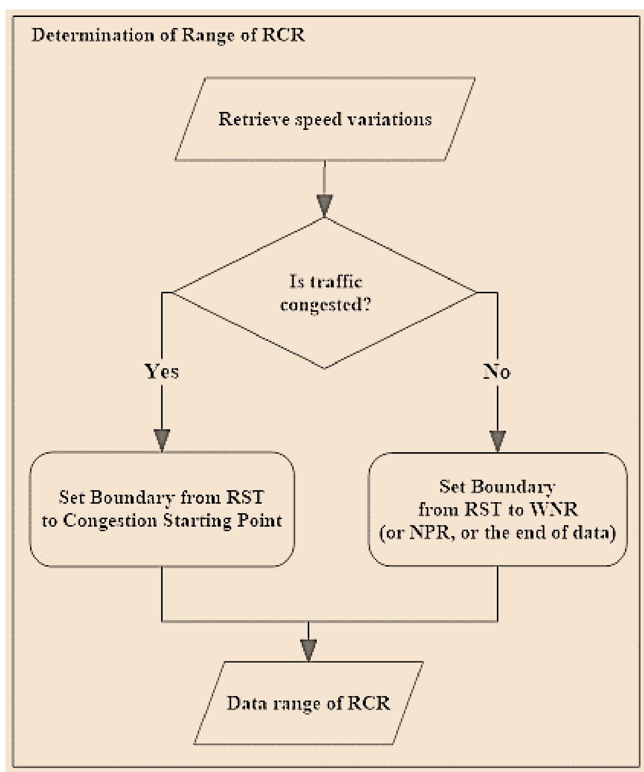

Figure 59: Process of Determination of Range of RCR

Step 2: Identification of Loop-Disturbance Patterns

The first type of traffic flow disturbance pattern, i.e., the "Loop-Disturbance Pattern" will be identified within the determined range of RCR. Based on the analysis in Chapter 4, the loop-disturbance patterns were featured to demonstrate a closed loop with at least one intersection point where the loop pattern lasted less than 30 minutes which is likely taken for the plowing truck to escape a snow section. Therefore, it will be pursued to find any closed loop with at least one intersection point where the loop pattern only remains less than 30 minutes before recovering the expected patterns in the UK planes. It should be noted that the closed-loop pattern can be found more than once during the recovery process and all possible points will be counted. The detail step-by-step is in the followings:

Step i) Select the consecutive pair of points for the reference points, i.e., $(K_1,\ U_1)$ and $(K_2,\ U_2)$ as the green points in Figure 60.

Step ii) Develop a linear equation between K and U that passes through the selected reference points in the form of Equation 23:

$$a_1 U + b_1 K + c_1 = 0$$

Equation 23

where, $a_1 = \frac{(U_2 - U_1)}{(K_2 - K_1)}$, $b_1 = -1$, and $c_1 = -a_1 + K_1$

Step iii) Select the next consecutive pair of points for the testing points, i.e., $(K_3,\ U_3)$ and $(K_4,\ U_4)$ as the red points in Figure 60.

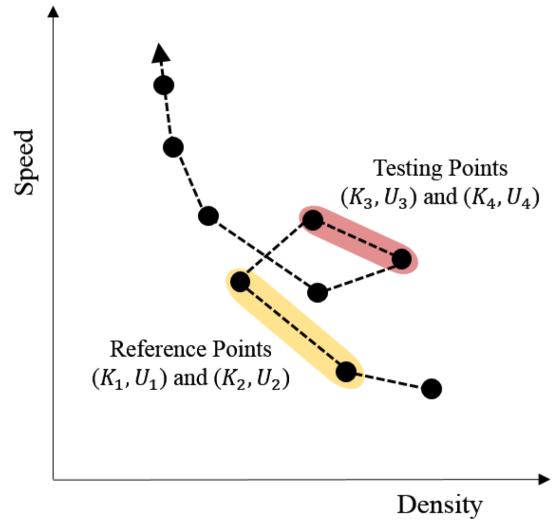

Figure 60: Selection of Reference Points and Testing Points in UK Diagrams

Step iv) Test if the segment of the reference points and the segment of the testing points are intersected using Equation 24 and Equation 25:

$$(a_1 U_3 + b_1 K_3 + c_1) \cdot (a_1 U_4 + b_1 K_4 + c_1) < 0$$

Equation 24

$$U_3 \le y \le U_4$$

$$\text{where, } y = \left(\frac{c_2}{a_2} - \frac{c_1}{a_1}\right) / \left(\frac{b_1}{a_1} - \frac{b_2}{a_2}\right)$$

Equation 25

The discriminative equation in Equation 24 was adopted for examining if the two given points are located in the other side of a given line. In addition to this, Equation 25 will allow to examine if the two segments share its intersection point. Validity of both Equation 24 and Equation 25 denotes the two selected segments intersect each other in the UK plane.

Step v) If intersection point is identified, assign the second point of the current testing point as a point of the loop-disturbance pattern.

Step vi) Continue to repeat the same process of Step (iii)-(v) by altering the testing points while keeping the consistent reference point for $\boldsymbol{\alpha}$ time intervals ($\boldsymbol{\alpha}$ =10) as appeared in Figure 61.

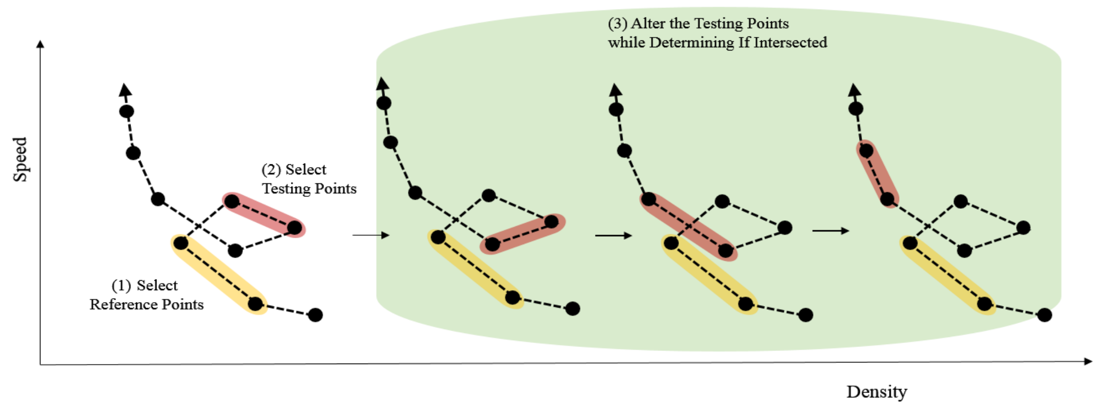

Figure 61: Alteration of Testing Points with Consistent Reference Points

Step vii) After the testing of $\boldsymbol{\alpha}$ time intervals ($\boldsymbol{\alpha}$=10), alter the reference points to the next two points to repeat Step (ii)-(vi) as shown in Figure 62.

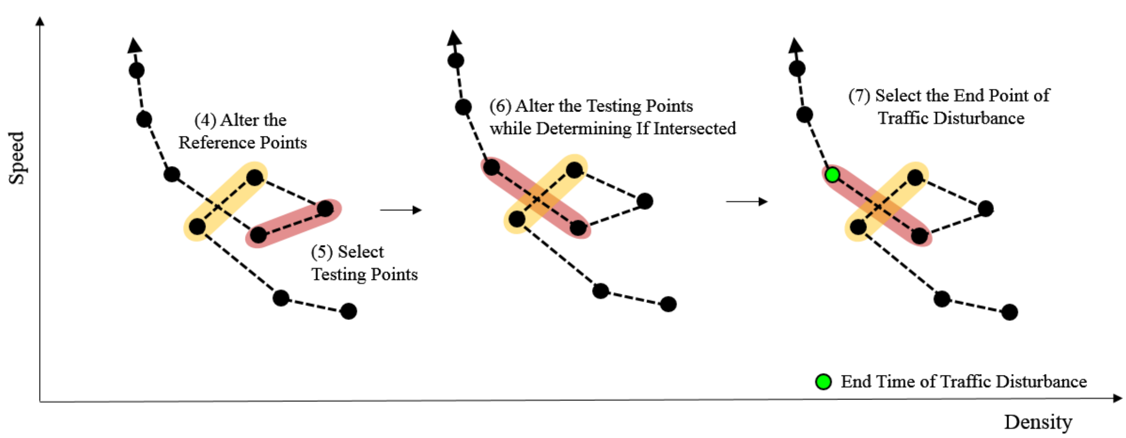

Figure 62: Alteration of Reference Points

Step viii) Continue Step (vii) within the boundaries of RCR.

The overall process for identifying the loop-disturbance patterns were presented as the flow chart in Figure 63 below.

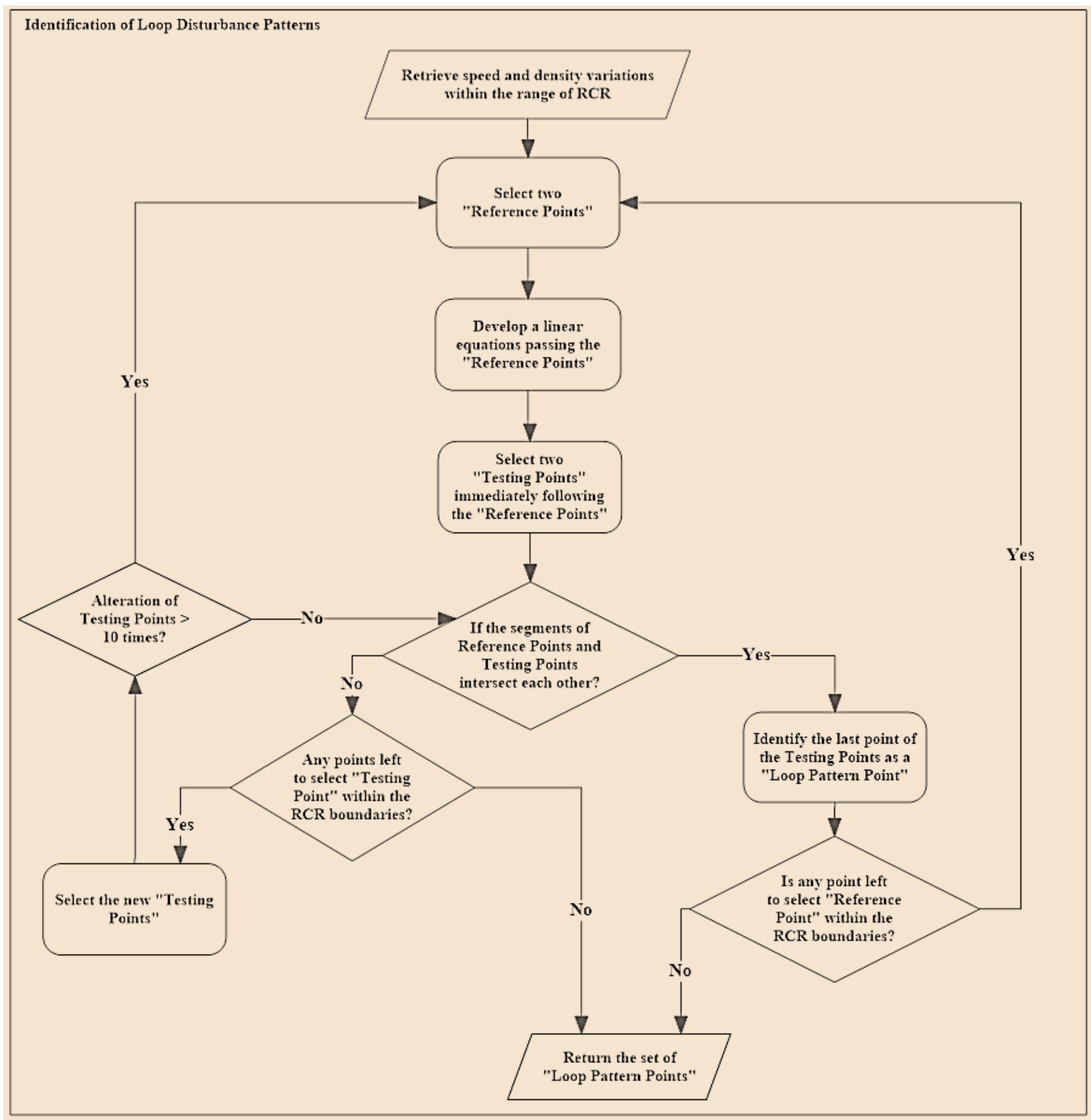

Figure 63: Flow Chart of Identification of Loop-Disturbance Patterns

Step 3: Identification of K-Disturbance Pattern

The second type of traffic disturbance pattern was the “K-Disturbance Pattern,” or Density-Disturbance Pattern. In the speed-density planes, as shown in Figure 64, it was featured to have an oscillation in density while speed sustained or increased during the disturbance period, which after the speed started increasing significantly. The traffic flow process of K-disturbance patterns were featured to have the typical patterns as followings:

(1) Speed sustains while density increases

(2) Density continues to increase

(3) Density turns to decreases while speed increases

(4) Speed increases significantly while density sustains

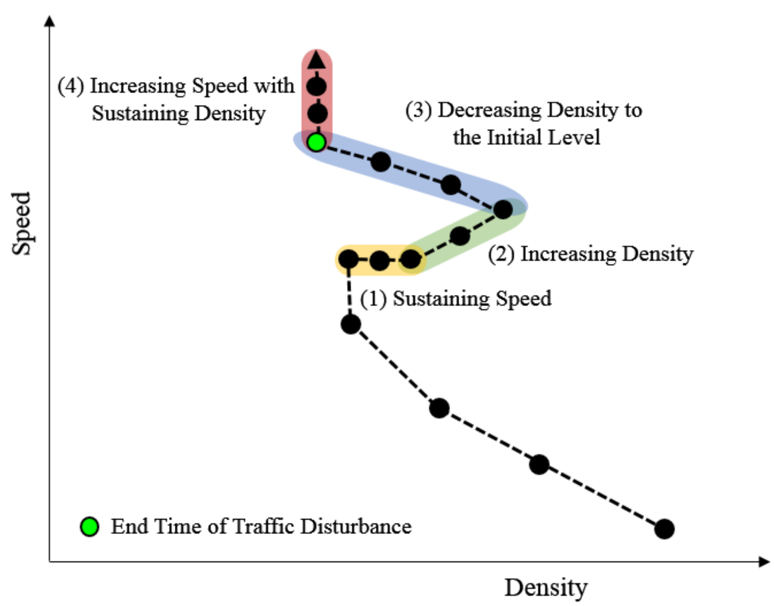

Figure 64: Traffic flow process of the K-disturbance pattern

The automatic process to identify the K-Disturbance Pattern was designed to search the speed and density variations independently. The algorithm was developed to identify the four subordinate patterns comprising the K-disturbance pattern in order. Similarly with the loop-disturbance pattern, the K-disturbance patterns can be found more than once within the recovery period for a given snow section. The step-by-step process was as followings:

Step i) Speed and density measurements at time t are rounded to the nearest integers in order to extract the trend of each variations, i.e., $K_{int,t}$ and $U_{int,\, t}$

Step ii) Within the boundaries of RCR, separately search the integerized speed and density variations to identify any patterns satisfying Equation 26. The conditions in Equation 26 pertain to the horizontal pattern in the speed-density plane, where speed sustains while density increases.

$$K_{t+1} \text{-} K_t > 0 \quad \text{and} \quad U_{int,\, t+1} - U_{int,\, t} = 0$$

Equation 26

Step iii) If any pattern is found in the previous step, continue searching to identify any patterns satisfying Equation 27 for $\boldsymbol{\alpha}$ time intervals ($\boldsymbol{\alpha}$=2). The conditions in Equation 27 denotes the increases both in speed and density.

$$K_{t+1} - K_t > 0 \quad \text{and} \quad U_{int,\, t+1} - U_{int,\, t} > 0$$

Equation 27

Step iv) If any pattern is found in the previous step, continue to search to identify if the density decreases by the level of pre-disturbance while speed continues to increase.

Step v) If any pattern is found in the previous step, continue to search to identify any patterns satisfying Equation 28. The conditions in Equation 28 pertains to the vertical pattern in the speed-density plane where speed increases while density sustains.

$$K_{int,\ t+1} - K_{int,\ t} = 0 \text{ and } U_{int,\ t+1} - U_{int,\ t} > 0$$

Equation 28

Step vi) If any pattern is found in the previous step, or all the four types of patterns are found in series, assign the starting point of the vertically increasing speed pattern which was identified in Step (v) as the end time of traffic disturbance.

Step vii) Iterate Step (ii)-(vi) within the boundaries of RCR.

The overall process for identifying the K-disturbance patterns were presented in the flow chart in Figure 65 below.

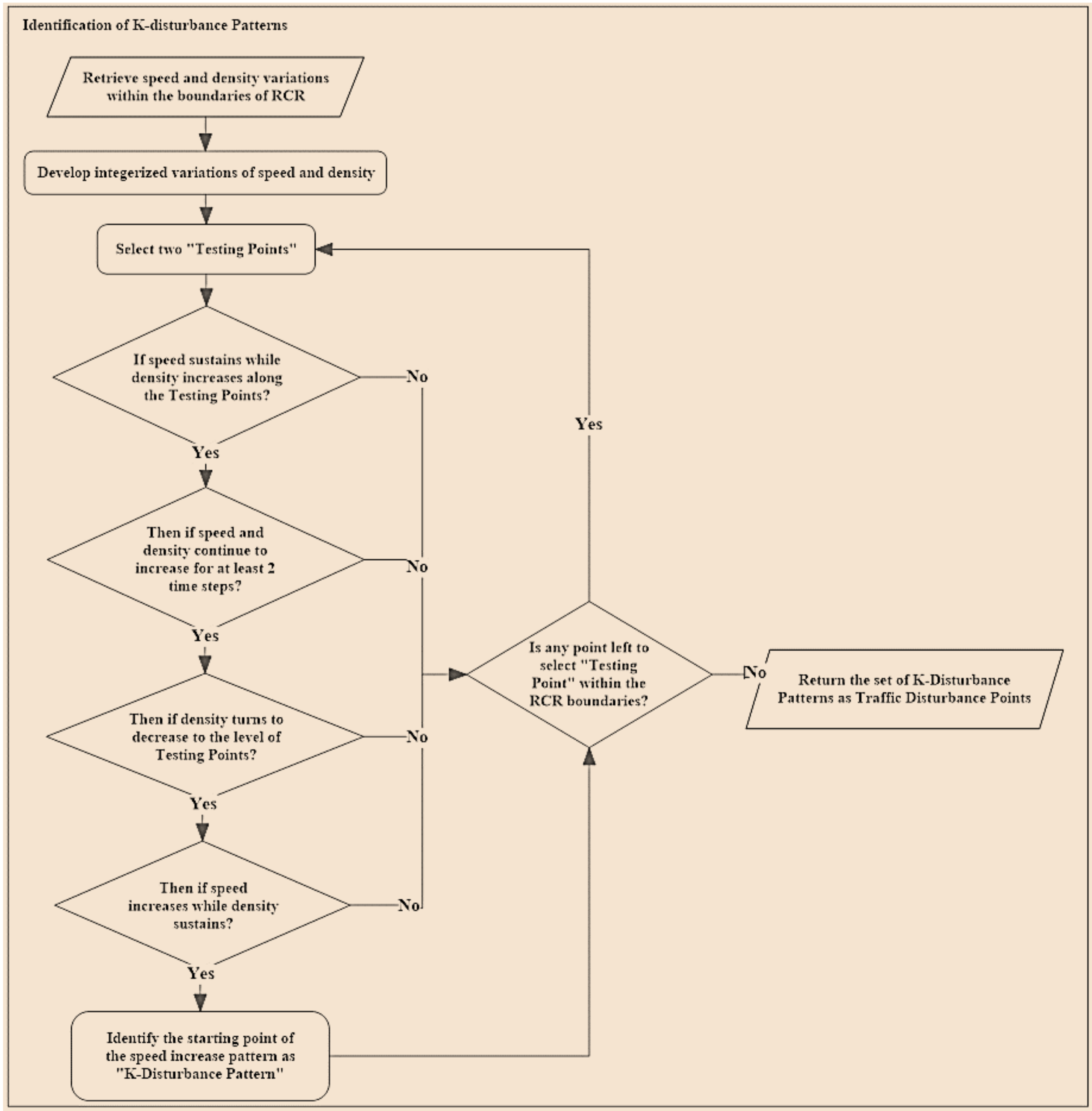

Figure 65: Flow Chart of Identification of K-Disturbance Patterns

Step 4: Identification of Vertical-Increasing Pattern

The last type of the traffic flow disturbance pattern was "Vertical-Increasing Pattern." As shown in Figure 66, this type of pattern was characterized to have a series of vertically increasing patterns in the speed-density planes after the pattern of maintaining speed. The traffic flow process of "Vertical-Increasing Pattern" consists of the two subordinate patterns in order as followings:

(1) Speed sustains while density decreases

(2) Speed increases while density sustains at least for 3 times

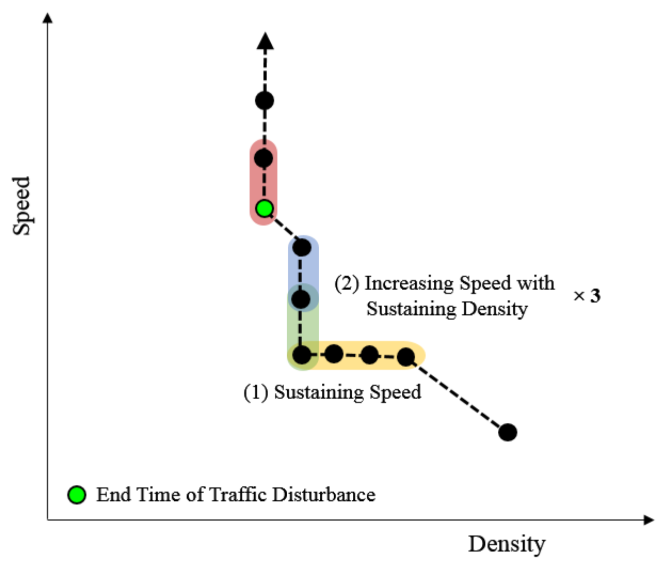

Figure 66: Traffic Flow Pattern of the Vertical-Increasing Pattern

Likewise the earlier type, the automatic process to identify the "Vertical-Increasing Pattern" was designed to search the speed and density variations independently. The algorithm was developed to identify the two subordinate patterns comprising the Vertical-

Increasing pattern in order. Similarly with the other types of traffic disturbance patterns, the Vertical-Increasing pattern can be found more than once within the recovery period for a given snow section. The step-by-step process was as followings:

Step i) Speed and density measurements at time t are rounded to the nearest integers in order to extract the trend of each variations, i.e., $K_{int,t}$ and $U_{int,\ t}$

Step ii) Within the boundaries of RCR, separately search the integerized speed and density variations to identify any patterns satisfying Equation 29. The conditions in Equation 29 pertain to the horizontal pattern in the speed-density plane, where speed sustains while density decreases.

$$K_{t+1}\text{-}\ K_t < 0 \text{ and } U_{int,\ t+1} - U_{int,\ t} = 0$$

Equation 29

Step iii) If any pattern is found in the previous step, continue searching to identify any patterns satisfying Equation 30 for $\boldsymbol{\alpha}$ time intervals ($\boldsymbol{\alpha}$ =3). The conditions in Equation 30 denotes the vertical pattern in the speed-density plane, where speed increases while density sustains.

$$K_{int,\ t+1} - K_{int,\ t} = 0 \text{ and } U_{int,\ t+1} - U_{int,\ t} > 0$$

Equation 30

Step iv) If any pattern is found in the previous step, or all the 2 types of patterns are found in series, assign the starting point of the vertically increasing speed pattern which was identified in Step (iii) as the end time of traffic disturbance.

Step v) Iterate Step (ii)-(iv) within the boundaries of RCR.

The overall process for identifying the vertical-increasing patterns were presented in the flow chart in Figure 67 below.

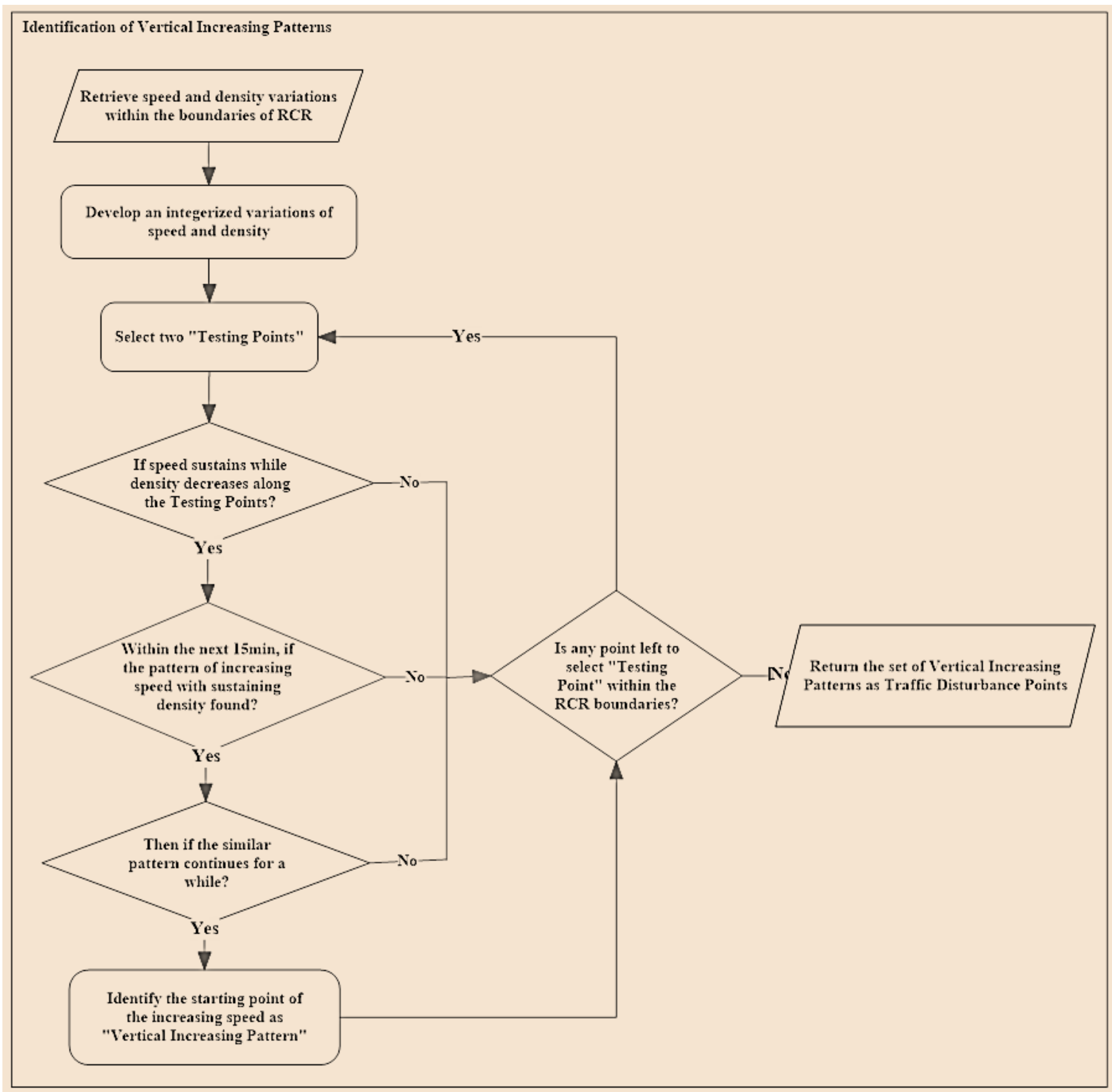

Figure 67: Flow Chart of Identification of Vertical-Increasing Patterns

Step 5: Identification of Snow Plowing Patterns

The three types of traffic disturbance patterns identified through **Step 2** to **Step 4** are to be integrated into a set of traffic disturbance patterns. In this step, each point of the traffic disturbance pattern will be examined to identify whether the pattern was resulted by the snow plowing operations or by the significant traffic volume variability. Based on the result, the patterns created along the significant reduction in traffic volumes will be eliminated to only reserve any snow plowing patterns to select RCR among them in the next step.

The automatic algorithm for identifying snow plowing patterns was designed to identify if the traffic volume variations ahead of each traffic disturbance points has been stable or showing negligible fluctuations to select such point as snow plowing patterns. If traffic volume variations ahead of a traffic disturbance point fail to show stable trend, it will be identified that the traffic disturbance was resulted by the transient variability of traffic volumes within the snow section. The step-by-step of the automatic algorithm for identifying snow plowing patterns is as followings:

Step i) Select the first point among the set of traffic disturbance pattern points.

Step ii) Retrieve the traffic volume variations from 4 time intervals ahead of the selected point to the selected point.

Step iii) Identify if the traffic volume variations meet the conditions in Equation 31Equation 32 which denotes the insignificant variations of traffic volumes prior to the traffic disturbance pattern. If so, the point is identified as the points of snow plowing pattern.

$N_{t+1} - N_t = 0$ for $\boldsymbol{\alpha}$ time interval ($\boldsymbol{\alpha}$=4), or
$N_{t+1} - N_t > 0$ for β time interval (β=1)

Equation 31

Step iv) Iterate Step (i)-(iii) while examining all points of traffic disturbance pattern points

The overall process for identifying the snow plowing patterns was presented in the flow chart in Figure 68 below.

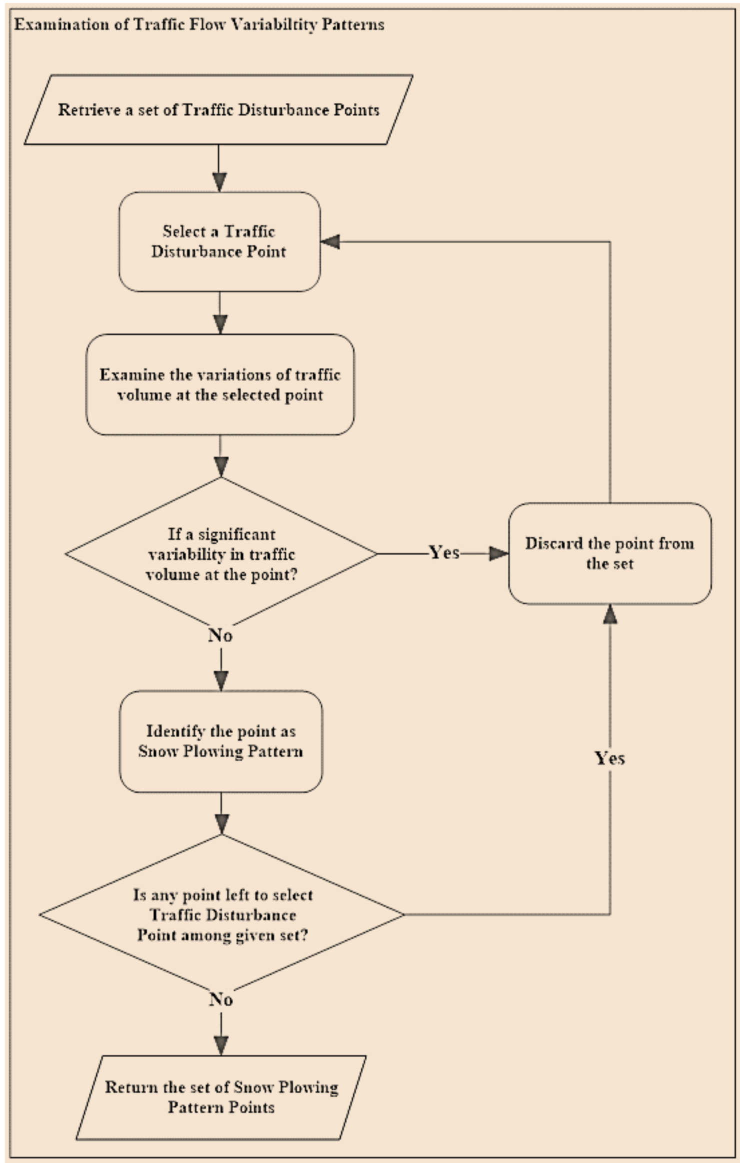

Figure 68: Flow Chart of Identification of Snow Plowing Patterns

Step 6: Identification of RCR

In this step, the point of Road Condition Recovery (RCR) is identified among the set of snow plowing pattern points identified in the previous step. Basically, RCR is identified as the last point before reaching the posted speed limit of the snow section, except the cases listed in the followings:

(1) If the speed at RST is already higher than the speed at PSR, the RST point is selected as RCR.

(2) In the case of traffic congestion, the last point of snow plowing pattern before WNR is selected as RCR.

(3) If none of patterns were observed before WNR, RST is selected as RCR.

The automatic algorithm for selecting RCR was designed in a way to examine the snow event case if it applies to any of the exceptional cases listed above. When the given snow event case does not pertain to any of the exceptional cases, RCR will be identified as the last snow plowing pattern point before PSR. Otherwise, RCR will be determined based on the each different logic. The detail step-by-step for identification of RCR is as followings:

Step i) Retrieve a set of snow plowing pattern points.

Step ii) Determine if Equation 32 satisfies for the given snow event. Satisfying the condition indicates the tenuous impact of snow on the traffic flow:

$$U(RST) \geq \text{Posted Speed Limit}$$

Equation 32

Step iii) If Step (ii) is true, RST is selected as RCR and terminate the process to select RCR. If not, proceed to Step (iv).

Step iv) Determine if traffic is congested during recovery period.

Step v) If Step (iv) is true, WNR is selected as RCR and terminate the process to select RCR. If not, proceed to Step (vi).

Step vi) Determine if any snow plowing patterns exists between RST and PSR.

Step vii) If Step (vi) is true, the last point before PSR is selected as RCR and terminate the process to select RCR. If not, proceed to Step (viii).

Step viii) Having none of additional snow plowing patterns within the recovery period, select RST as RCR and terminate the algorithm.

The overall process of identification of RCR was presented in the flow chart in Figure 69 below.

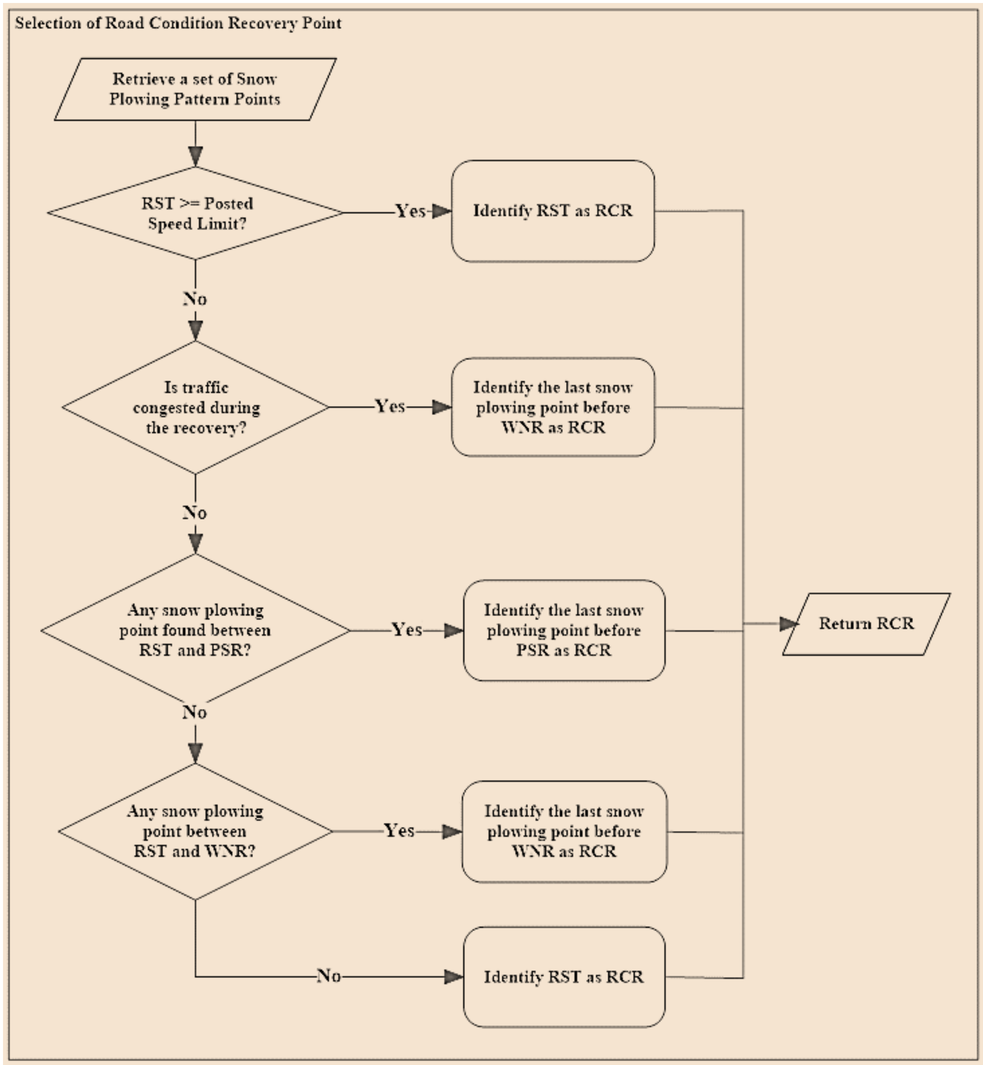

Figure 69: Flow Chart of Identification of RCR

5.4.3. Testing of RCR

Method of algorithm evaluation

In this section, it will be discussed the method to evaluate the algorithm for estimating RCR developed in the previous sections. The traffic data on the selected snow event cases for this study will be employed in applying the algorithm, and the estimated RCR for each snow event case will be compared with the "True RCR." As mentioned earlier in the previous chapter, the reported bare lane regain time imposes an issue of objectivity as the plowing operators determine the bare lane regain time based on their visual inspections. Also, one bare lane regain time is reported for one snow route, so it is not likely that the different progress of road condition recovery within the different snow sections consisting a same snow route are fully reflected. In fact, it was observed that the speed at the reported bare regain time mostly exceed the posted speed limit, which is not consistent with the definition of bare lane regain time defined by MnDOT. To address this issue, it was identified the "true RCR" for each case through the visual assessment on the SFDs to use the time as an alternative reference point of evaluation. The process to identify the "true RCR" is as following:

1) Define the range of road condition recovery, e.g., from RST to PSR in case of the recovery to the free flow condition; from RST to WNR in case of the recovery to the congested traffic flow.
2) Identify the traffic flow disturbance patterns within the range.

3) Distinguish the pattern resulted by snow plowing operations and the pattern resulted by the traffic flow variability by examining the variations of traffic flow.

4) Among the snow plowing operations patterns, select the last point as a true RCR.

Testing results

In this section, the test results of the algorithm will be presented. Table 4 shows the difference between the estimated RCR and the "True RCR" for each snow event case. Based on this, the distribution of the difference was plotted in Table 5 and Figure 70 below.

Table 4: Difference between the estimated RCR and the true RCR

Snow Event	Snow Section	Estimated RCR	True RCR	Reported Bare-lane Time	Difference of True and Estimated RCRs (min)
19 Nov, 2011	35E NB	19:09	19:09	17:30	0
19 Nov, 2011	35E SB	18:24	18:12	17:30	12
19 Nov, 2011	694 EB	18:30	18:27	17:30	3
19 Nov, 2011	694 WB	18:09	18:12	17:30	3
14 Jan, 2012	35E NB	17:39	17:39	17:00	0
14 Jan, 2012	35E SB	17:30	17:30	17:00	0
14 Jan, 2012	694 EB	16:48	16:48	17:00	0
14 Jan, 2012	694 WB	14:51	14:51	17:00	0
14 Jan, 2012	94 EB	19:57	20:00	23:30	3
14 Jan, 2012	94 WB	19:57	19:54	23:30	3
14 Jan, 2012	52 NB	16:42	17:05	23:30	63
14 Jan, 2012	52 SB	16:30	16:30	23:30	0
20 Jan, 2012	35E NB	13:36	13:45	13:15	9
20 Jan, 2012	35E SB	13:09	13:15	13:15	6
20 Jan, 2012	694 EB	13:06	13:03	13:15	3
20 Jan, 2012	694 WB	14:51	14:57	13:15	6
20 Jan, 2012	94 EB	13:24	13:48	13:15	24
20 Jan, 2012	94 WB	14:54	14:51	13:15	3
20 Jan, 2012	52 NB	14:57	14:48	13:15	9
20 Jan, 2012	52 SB	13:54	13:57	13:15	3

23 Jan, 2012	35E NB	10:03	10:03	11:00	0
23 Jan, 2012	35E SB	10:15	10:15	11:00	0
23 Jan, 2012	694 EB	09:33	9:36	11:00	3
23 Jan, 2012	694 WB	10:24	10:42	11:00	18
23 Jan, 2012	94 EB	10:39	10:48	11:00	9
23 Jan, 2012	94 WB	10:00	10:00	11:00	0
23 Jan, 2012	52 NB	09:42	10:27	11:00	45
23 Jan, 2012	52 SB	10:48	10:45	11:00	3
29 Feb, 2012	35E NB	09:30	9:18	9:09	12
29 Feb, 2012	35E SB	10:21	10:30	9:09	9
29 Feb, 2012	694 EB	10:21	10:27	9:09	6
29 Feb, 2012	694 WB	10:24	10:39	9:09	15
29 Feb, 2012	94 EB	09:45	9:54	9:09	6
29 Feb, 2012	94 WB	09:30	09:30	9:09	0
29 Feb, 2012	52 NB	09:24	8:57	9:09	27
29 Feb, 2012	52 SB	07:03	7:33	9:09	30
22 Feb, 2013	35E NB	10:15	10:15	10:30	0
22 Feb, 2013	35E SB	10:27	10:36	10:30	9
22 Feb, 2013	694 EB	09:51	9:54	10:30	3
22 Feb, 2013	694 WB	10:00	10:09	10:30	9
22 Feb, 2013	94 EB	10:57	11:21	11:00	24
22 Feb, 2013	94 WB	08:36	10:24	11:00	108
22 Feb, 2013	52 NB	09:00	9:06	11:00	6
22 Feb, 2013	52 SB	09:36	10:27	11:00	51
14 Mar, 2013	35E NB	08:27	8:36	9:30	9
14 Mar, 2013	35E SB	09:00	9:21	9:30	21
14 Mar, 2013	694 EB	08:12	9:00	9:30	48
14 Mar, 2013	694 WB	09:15	9:27	9:30	12
18 Mar, 2013	35E NB	11:39	11:39	12:00	0
18 Mar, 2013	35E SB	11:27	11:27	12:00	0
18 Mar, 2013	694 EB	11:42	11:42	12:00	0
18 Mar, 2013	694 WB	12:51	12:51	12:00	0
18 Mar, 2013	94 EB	11:06	11:06	10:00	0
18 Mar, 2013	94 WB	10:51	11:24	10:00	33
18 Mar, 2013	52 NB	11:36	11:36	10:00	0
18 Mar, 2013	52 SB	10:27	10:30	10:00	3

Based on the result of the evaluation, it was observed that the 40 cases out of 56 cases showed the time difference less than 10 minutes from the True RCR, and almost 90% of the total cases had the difference less than 30 minutes from the True RCR.

Table 5: Distribution of the time difference between the estimated RCR and the "True RCR"

Difference (min)	Number of cases
10	40
20	5
30	5
40	1
50	2
60	1
≥ 60 min	2
Total	56

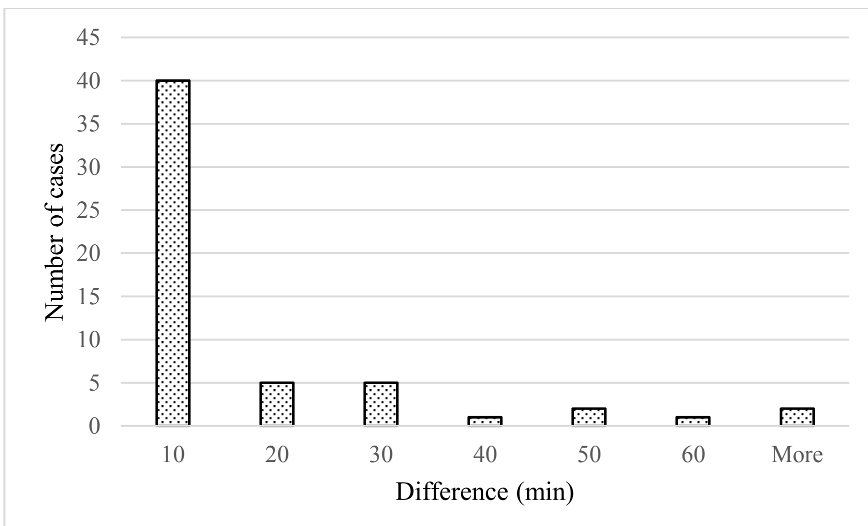

Figure 70: Distribution of the time difference between the estimated RCR and the "True RCR"

5.5. Development of an Automatic Process for Estimating the Operational Measures

In this section, it will be stated an automatic process for estimating the operational measures developed in the previous chapter. The general process is as shown in Figure 71 below. The input and output for this subordinate process is summarized as followings:

- Input: The phase change points

  Section-wide speed variations during the given snow event

  Section-wide speed variations of average dry normal days

- Output: A set of user-defined operational measures for winter snow management

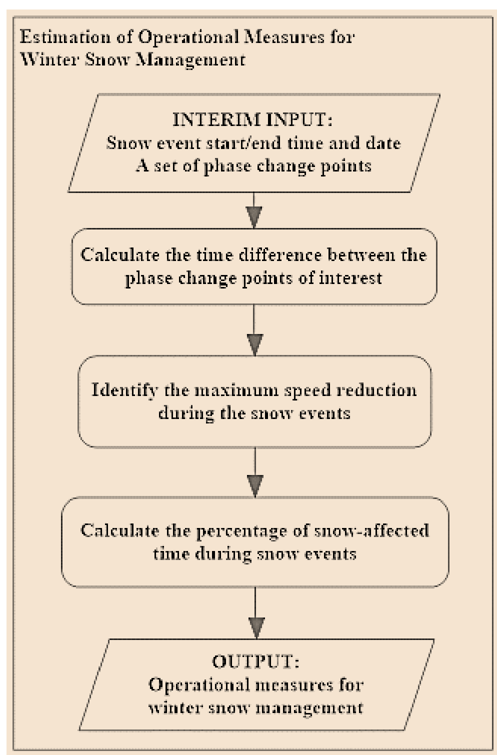

Figure 71: Subordinate Process of Estimation of Operational Measures

As noticed based on the definition of each operational measure, process to estimate each operational measure only requires the simple calculations using the information of the points of interests. First, the operational measures of time duration between two phase change points were estimated in the following steps:

Step 1: Receive the two points of interests from the user.

Step 2: Calculate the time difference between the selected points as in Equation 33 below:

Time duration between the points of interest = t $(Point_1)$ – t $(Point_2)$

Equation 33

Next, the operational measure of the maximum speed reduction at LST was estimated in the following steps:

Step 1: Retrieve the dry-normal speed variations comparable to the snow event time.

Step 2: Obtain the speed at LST within the snow-affected speed variations.

Step 3: Obtain the speed of the same time with the LST within the dry-normal speed variations

Step 4: Calculate the speed difference between the cases of snow event and an average pattern of dry-normal days as in Equation 34:

Maximum speed reduction at LST = $\mathrm{U_{dry}(LST) - U_{snow}(LST)}$

Equation 34

For the last type of operational measure, the ratio of snow-affected time to snow event duration was estimated in the following steps:

Step 1: Retrieve the dry-normal speed variations comparable to the snow event time.

Step 2: Receive the threshold for determining the "acceptable dry-normal speed level."

Step 3: Identify the intervals where the speed became less than the "acceptable dry-normal speed level."

Step 4: Add up the total intervals to obtain the "snow-affected time duration."

Step 5: Calculate the snow event duration by calculating the gap between the snow start and end time.

Step 6: Calculate the ratio of the "snow-affected time duration" to the snow event duration as in Equation 35:

$$\text{Ratio of snow-affected duration} = \frac{(\text{Snow}-\text{Affected Time Duration})}{(\text{Snow Event Duration})}$$

Equation 35

CHAPTER 6: EXAMPLE APPLICATION OF AUTOMATIC PROCESS WITH SAMPLE SNOW SECTION

In the previous chapter, an automatic process was developed for estimating the traffic data-based operational measures for winter snow management. The input of the algorithm included the snow event start/end time and the traffic data collected from the loop detectors in the highways. The output of the algorithm was a set of the traffic data-based operational measures which were defined using the phase change points.

In Chapter 6, the automatic process for estimating operational measures will be applied to the sample snow section and the results will be presented in the following order:

6.1 Overview of Application Process

6.2 Example Estimation of Operational Measures for Sample Snow Section

6.1. Overview of Application Process

The automatic process for estimating the operational measures was integrated into the software named TICAS (Traffic Information and Condition Analysis System) developed by the research group at the University of Minnesota Duluth.

The input data of the algorithm includes the snow event start/end time and the configuration of a given snow section, i.e., the boundaries of the snow section. Those input information is inserted as shown in Figure 72 below.

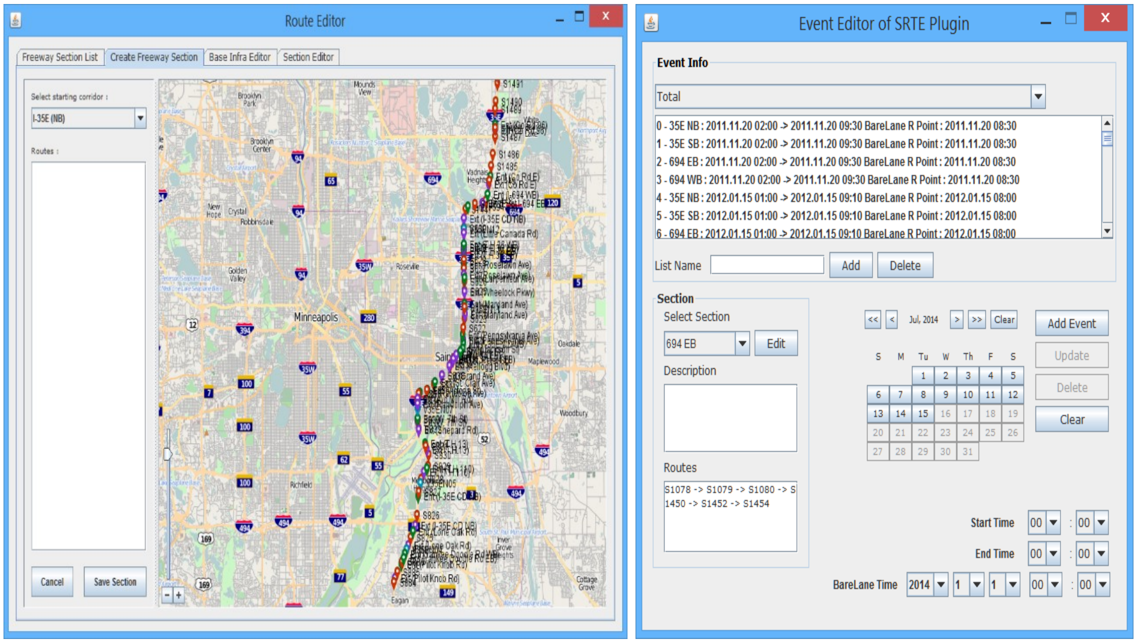

Figure 72: Editor Window for Route (Left) and Snow Event (Right)

The output of the algorithm has two types of formats: Excel format and the graphical format. The excel format of output includes the summary results for all snow sections defined in the "Event List." The summary results in the excel file comprises of the following items as shown in Figure 73.

- Time and speed of each phase change point, i.e., SRST, LST, RST, RCR, PSR, WNR and NPR
- Operational measures for the given snow section for each snow event

	A	B	C	D	E	G	H	J	L	M	N	P	Q	R	T	U
1		Snow event info:							Phase change points:							
2	Section name	i(Snow start)	t(Snow start)	i(Snow end)	t(Snow end)	i(Bare lane)	t(Bare lane)	Speed limit (SLP)	i(SRST)	t(SRST)	U(SRST)	i(LST)	t(LST)	U(LST)	i(RST)	t(R
3	35E NB - 1	39	19 Nov, 2011 at 11:00:00	189	19 Nov, 2011 at 18:30:00	169	19 Nov, 2011 at 17:30:00	206	38	10:57	67.13028	76	12:51	43.22	76	12:
4	35E SB - 2	39	19 Nov, 2011 at 11:00:00	189	19 Nov, 2011 at 18:30:00	169	19 Nov, 2011 at 17:30:00	199	47	11:24	67.04382	77	12:54	44.1	77	12:
5	694 EB - 3	39	19 Nov, 2011 at 11:00:00	189	19 Nov, 2011 at 18:30:00	169	19 Nov, 2011 at 17:30:00	183	38	10:57	74.99335	159	17:00	49.75	178	17:
6	694 WB - 4	39	19 Nov, 2011 at 11:00:00	189	19 Nov, 2011 at 18:30:00	169	19 Nov, 2011 at 17:30:00	186	43	11:12	74.7441	163	17:12	45.67	163	17:
7	35E NB - 5	39	14 Jan, 2012 at 10:00:00	203	14 Jan, 2012 at 18:10:00	179	14 Jan, 2012 at 17:00:00	192	104	13:15	69.76172	192	17:39	59.14	192	17:
8	35E SB - 6	39	14 Jan, 2012 at 10:00:00	203	14 Jan, 2012 at 18:10:00	179	14 Jan, 2012 at 17:00:00	189	91	12:36	68.56217	189	17:30	57.83	189	17:
9	694 EB - 7	39	14 Jan, 2012 at 10:00:00	203	14 Jan, 2012 at 18:10:00	179	14 Jan, 2012 at 17:00:00	175	108	13:27	78.65724	175	16:48	64.58	175	16:
10	694 WB - 8	39	14 Jan, 2012 at 10:00:00	203	14 Jan, 2012 at 18:10:00	179	14 Jan, 2012 at 17:00:00	136	106	13:21	76.41115	136	14:51	63.45	136	14:
11	94 EB - 9	39	14 Jan, 2012 at 10:15:00	203	14 Jan, 2012 at 18:25:00	264	14 Jan, 2012 at 21:30:00	239	108	13:42	64.20183	214	19:00	32.26	214	19:
12	94 WB - 10	39	14 Jan, 2012 at 10:15:00	203	14 Jan, 2012 at 18:25:00	264	14 Jan, 2012 at 21:30:00	237	109	13:45	62.17487	164	16:30	41.38	233	19:
13	52 NB - 11	39	14 Jan, 2012 at 10:15:00	203	14 Jan, 2012 at 18:25:00	264	14 Jan, 2012 at 21:30:00	168	108	13:42	73.07495	168	16:42	54.43	168	16:
14	52 SB - 12	39	14 Jan, 2012 at 10:15:00	203	14 Jan, 2012 at 18:25:00	264	14 Jan, 2012 at 21:30:00	173	63	11:27	67.10068	164	16:30	47.04	164	16:
15	35E NB - 13	39	20 Jan, 2012 at 06:15:00	189	20 Jan, 2012 at 13:45:00	179	20 Jan, 2012 at 13:15:00	193	40	06:18	67.8689	132	10:54	47.79	132	10:
16	35E SB - 14	39	20 Jan, 2012 at 06:15:00	189	20 Jan, 2012 at 13:45:00	179	20 Jan, 2012 at 13:15:00	183	38	06:12	67.93531	78	08:12	26.85	78	08:
17	694 EB - 15	39	20 Jan, 2012 at 06:15:00	189	20 Jan, 2012 at 13:45:00	179	20 Jan, 2012 at 13:15:00	181	38	06:12	77.92259	158	12:12	46.46	158	12:
18	694 WB - 16	39	20 Jan, 2012 at 06:15:00	189	20 Jan, 2012 at 13:45:00	179	20 Jan, 2012 at 13:15:00	220	42	06:24	72.92574	69	07:45	24.9	211	14:
19	94 EB - 17	39	20 Jan, 2012 at 06:15:00	189	20 Jan, 2012 at 13:45:00	179	20 Jan, 2012 at 13:15:00	285	38	06:12	55.36681	170	12:48	30.13	170	12:
20	94 WB - 18	39	20 Jan, 2012 at 06:15:00	189	20 Jan, 2012 at 13:45:00	179	20 Jan, 2012 at 13:15:00	219	41	06:21	59.28527	103	09:27	23.78	103	09:
21	52 NB - 19	39	20 Jan, 2012 at 06:15:00	189	20 Jan, 2012 at 13:45:00	179	20 Jan, 2012 at 13:15:00	213	44	06:30	67.70083	78	08:12	22.35	198	14:
22	52 SB - 20	39	20 Jan, 2012 at 06:15:00	189	20 Jan, 2012 at 13:45:00	179	20 Jan, 2012 at 13:15:00	198	40	06:18	64.94575	168	12:42	39.11	168	12:
23	35E NB - 21	39	23 Jan, 2012 at 05:00:00	149	23 Jan, 2012 at 10:30:00	159	23 Jan, 2012 at 11:00:00	155	38	04:57	58.37801	115	08:48	41.3	115	08:
24	35E SB - 22	39	23 Jan, 2012 at 05:00:00	149	23 Jan, 2012 at 10:30:00	159	23 Jan, 2012 at 11:00:00	153	38	04:57	57.32016	109	08:30	25.39	109	08:
25	694 EB - 23	39	23 Jan, 2012 at 05:00:00	149	23 Jan, 2012 at 10:30:00	159	23 Jan, 2012 at 11:00:00	153	38	04:57	66.29932	86	07:21	34.78	123	09:
26	694 WB - 24	39	23 Jan, 2012 at 05:00:00	149	23 Jan, 2012 at 10:30:00	159	23 Jan, 2012 at 11:00:00	143	38	04:57	66.07616	84	07:15	19.61	140	10:
27	94 EB - 25	39	23 Jan, 2012 at 05:00:00	149	23 Jan, 2012 at 10:30:00	159	23 Jan, 2012 at 11:00:00	155	38	04:57	54.0683	108	08:27	27.63	108	08:
28	94 WB - 26	39	23 Jan, 2012 at 05:00:00	149	23 Jan, 2012 at 10:30:00	159	23 Jan, 2012 at 11:00:00	154	38	04:57	49.75031	104	08:15	19.65	104	08:
29	52 NB - 27	39	23 Jan, 2012 at 05:00:00	149	23 Jan, 2012 at 10:30:00	159	23 Jan, 2012 at 11:00:00	140	38	04:57	50.9588	93	07:42	37.21	137	09:
30	52 SB - 28	39	23 Jan, 2012 at 05:00:00	149	23 Jan, 2012 at 10:30:00	159	23 Jan, 2012 at 11:00:00	158	38	04:57	53.76159	88	07:27	41.54	88	07:
31	35E NB - 29	39	29 Feb, 2012 at 05:00:00	144	29 Feb, 2012 at 10:15:00	122	29 Feb, 2012 at 09:09:00	131	38	04:57	45.25476	73	06:42	37.1	73	06:
32	35E SB - 30	39	29 Feb, 2012 at 05:00:00	144	29 Feb, 2012 at 10:15:00	122	29 Feb, 2012 at 09:09:00	151	38	04:57	50.92723	82	07:09	22.36	82	07:
33	694 EB - 31	39	29 Feb, 2012 at 05:00:00	144	29 Feb, 2012 at 10:15:00	122	29 Feb, 2012 at 09:09:00	151	38	04:57	54.89119	61	06:06	31.25	139	10:

Sheet1

Figure 73: Example Output of the Algorithm

Also, the graphical output of the module includes the following items:

- Section-wide speed and density variations during the given snow event
- Section-wide speed variations of average dry-normal days
- Section-wide Fundamental Diagrams (SFD) for the given snow section during snow event
- Exhibition of the phase change points within each type of variations plot during snow event

Figure 74 shows the example case of the graphical output including the two types of speed variations of snow events and average dry-normal days. In the graph, the red line indicates the snow-affected speed variations, and the black line indicates the dry-normal speed variations. Also, phase change points and snow event information are marked with its own identifications: Grey line indicates the snow event start/end time; Blue lines indicate SRST, LST and RST; Red line indicate RCR; Cyan line indicate WNR; Black line indicate NPR; Yellow line indicate the reported bare lane regain time.

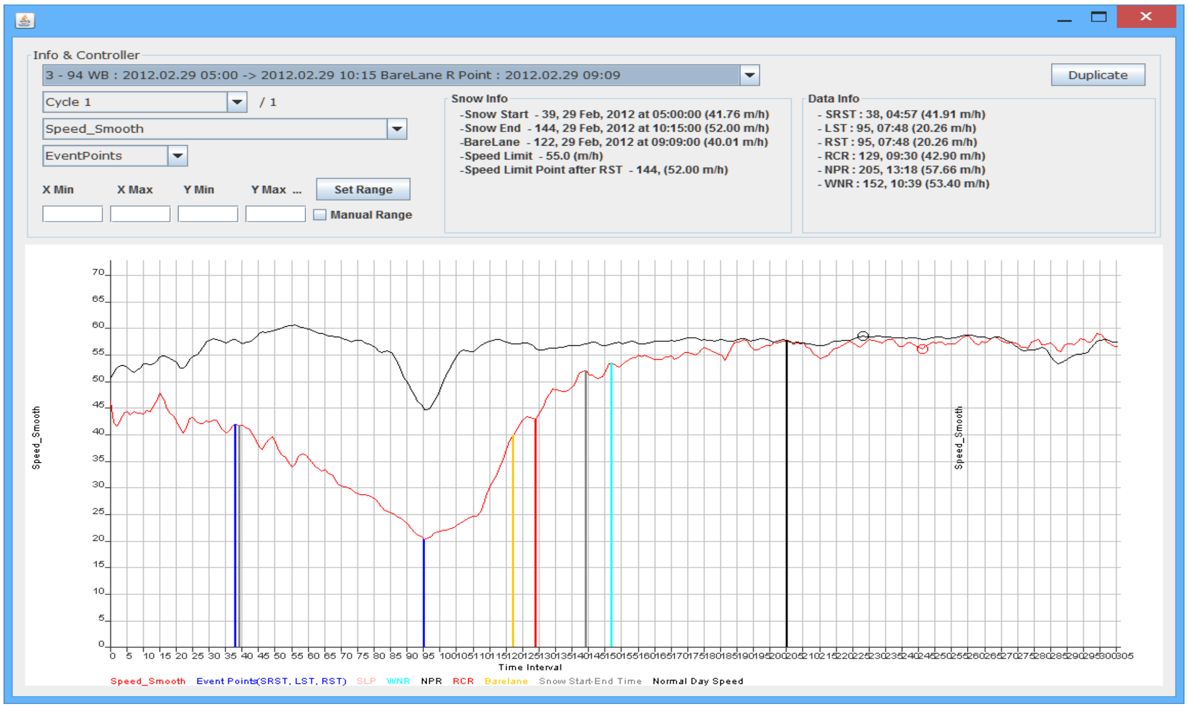

Figure 74: Example Case of Graphical Output including the Speed Variation with Phase Change Points

6.2. Example Estimation of Operational Measures for the Sample Snow Section

In this section, it will be provided the output result of traffic data-based operational measures for the sample snow section. As appeared in Figure 75, the both directional ways of the snow sections in TH.94, i.e., the eastbound and westbound snow sections of the TH.94, were selected for the sample areas. The operational measures developed in this study were estimated for the selected snow events during January, 2012 – March, 2013 as in Table 6 below. It should be mentioned that the section-wide traffic flow level at each snow section of the TH.94, which plays an important role in the process of the road recovery process, showed insignificant difference to each other during the selected snow events as appeared in Figure 76-Figure 80.

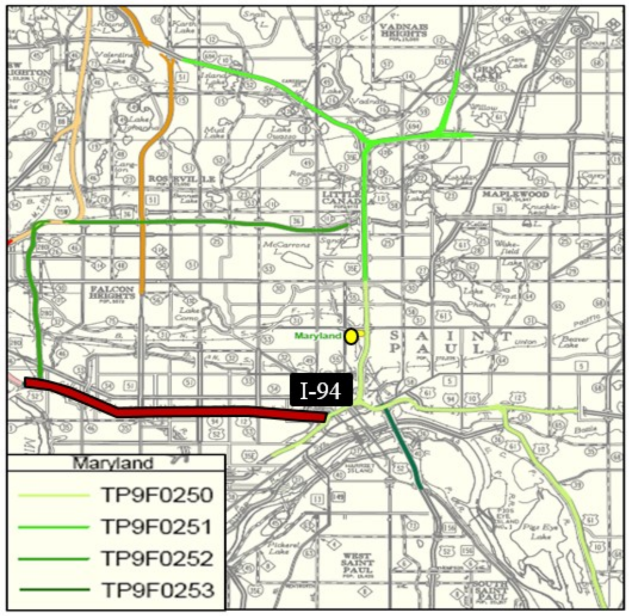

Figure 75: Sample Snow Section within the TH.94

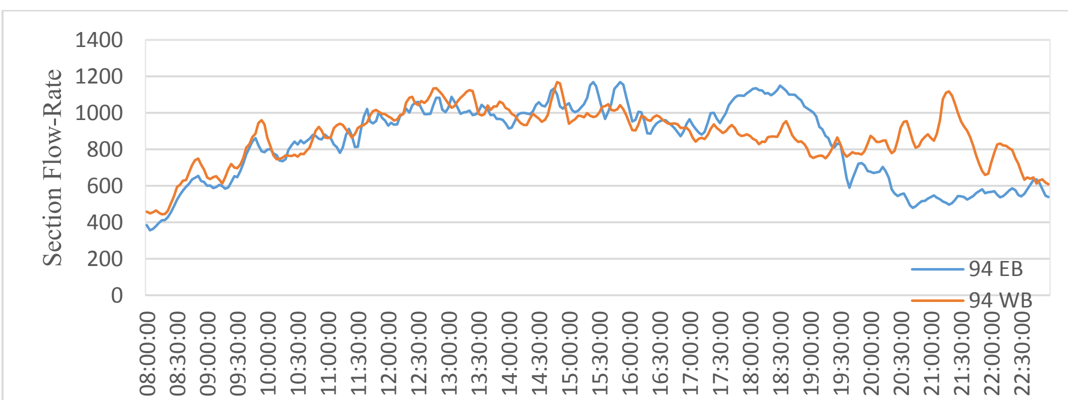

Figure 76: Section-wide Flow-rate of Each Snow Section on the Jan. 14. 2012

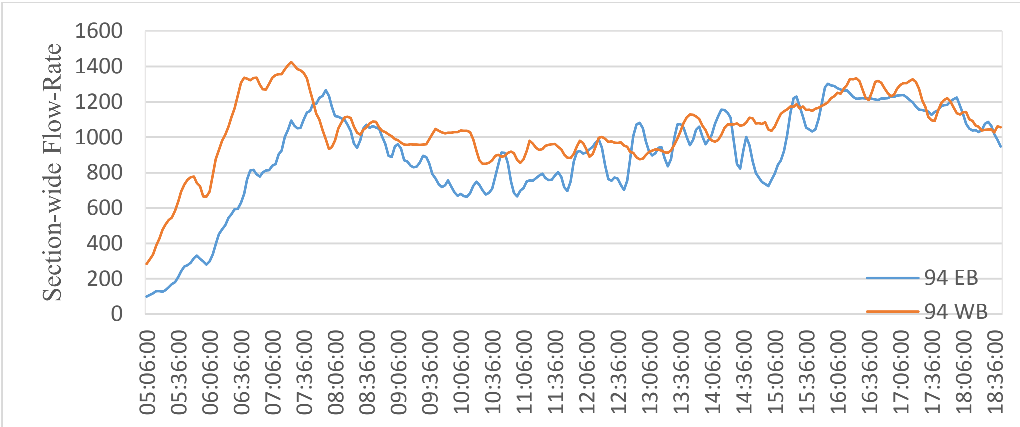

Figure 77: Section-wide Flow-rate of Each Snow Section on the Jan. 20. 2012

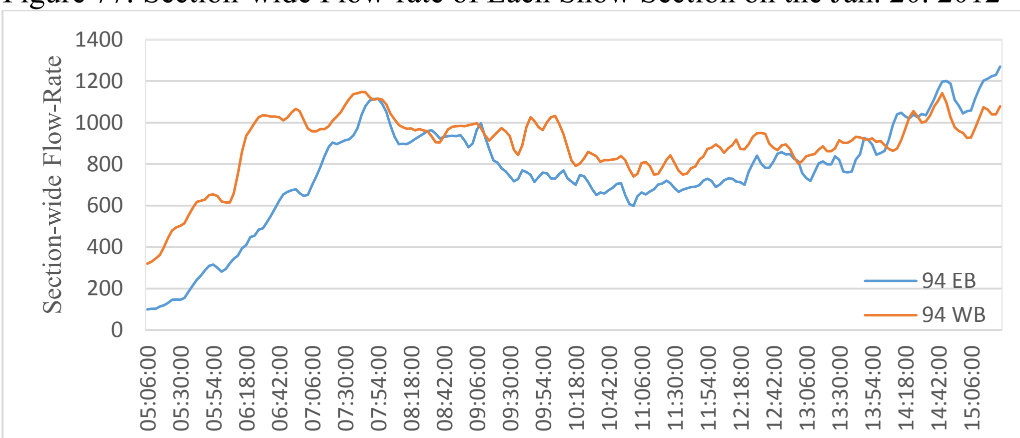

Figure 78: Section-wide Flow-rate of Each Snow Section on the Jan. 23. 2012

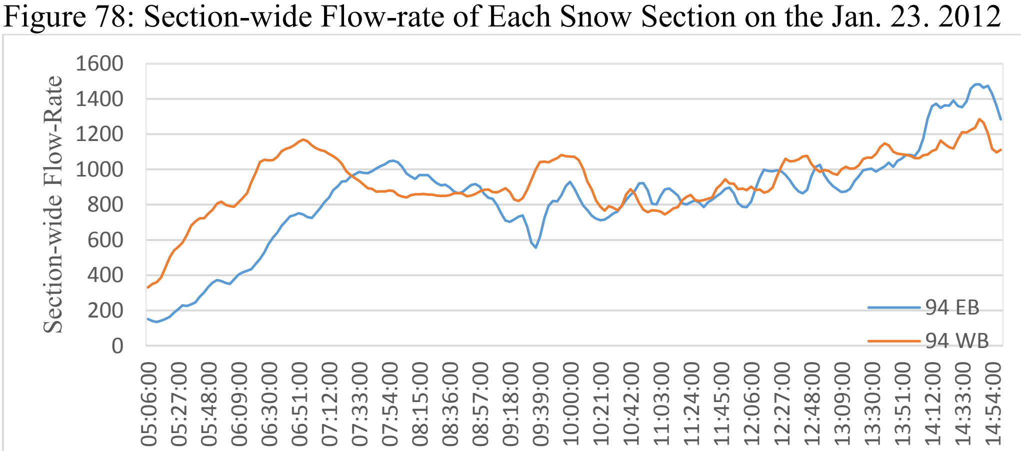

Figure 79: Section-wide Flow-rate of Each Snow Section on the Feb. 22. 2013

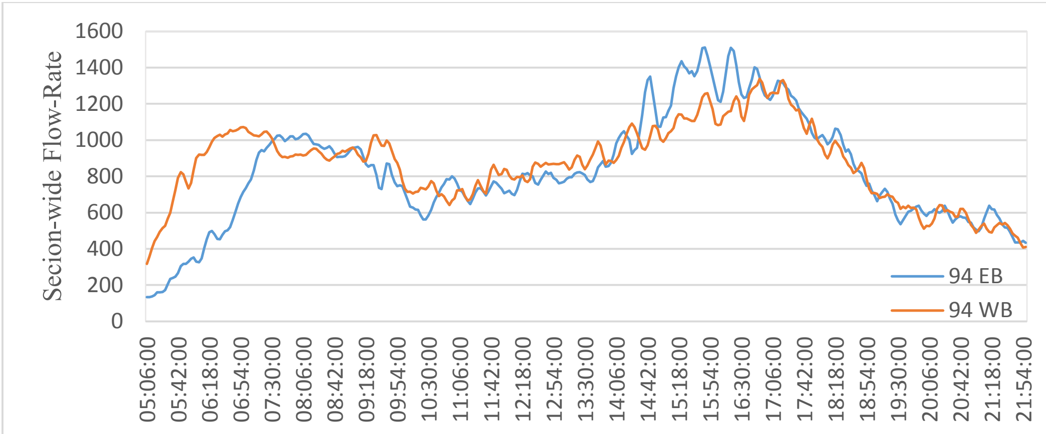

Figure 80: Section-wide Flow-rate of Each Snow Section on the Mar. 18. 2013

Table 6: Selected Snow Event Cases for the Example Application of Algorithm

	Snow Event Start Time		Snow Event End Time		Lane Regain Time	
1	1/14/2012 (Sat)	10:15	1/14/2012 (Sat)	18:25	1/14/2012 (Sat)	21:30
2	1/20/2012 (Fri)	6:15	1/20/2012 (Fri)	13:45	1/20/2012 (Fri)	13:15
3	1/23/2012 (Mon)	1:30	1/23/2012 (Mon)	10:30	1/23/2012 (Mon)	11:00
4	2/22/2013 (Fri)	1:00	2/22/2013 (Fri)	10:15	2/22/2013 (Fri)	11:00
5	3/18/2013 (Mon)	4:30	3/18/2013 (Mon)	17:00	3/18/2013 (Mon)	10:00

Table 7 shows the result of the operational measures for the winter snow management conducted on the snow section of TH.94 for the given snow events. The "0" for the operational measure of time difference indicates that the two selected phase change points coincide with each other. Also, it was represented as "-", when either side of the phase change point was not identified. It should be mentioned that WNR and NPR is not necessarily identified within the data range extracted due to the feature of winter snow management operations. It should be recalled that the threshold for the "acceptable speed level" was determined as 80% of the average dry-normal speed level when the "Ratio of snow-affected time" was estimated. Figure 81-Figure 90 provide the result of operational measures visually for each case of the selected snow events.

Table 7: Example Result of the Operational Measures for the Snow Management within TH.94 for Each Snow Event

	94EB					94WB				
Operational Measures	1/14/2012	1/20/2012	1/23/2012	2/22/2013	3/18/2013	1/14/2012	1/20/2012	1/23/2012	2/22/2013	3/18/2013
Snow start time - SRST	3h 27min	-3min	0	0	-3min	3h 30min	6 min	-3min	0	-3min
SRST - LST	5h 18min	6h 36min	7h	8h 57min	3h 12min	2h 45min	3h 6min	6h 48min	7h 24min	3h 9min
SRST - RST	5h 18min	6h 36min	7h	8h 57min	3h 12min	6h 12min	3h 6min	6h 48min	7h 24min	3h 9min
SRST - RCR	6h 15min	7h 12min	9h 12min	9h 57min	6h 9min	6h 12min	8h 33min	8h 33min	7h 33min	5h 54min
SRST - WNR	6h 42min	8h 3min	10h 33min	10h 36min	6h 54min	6h 36min	8h 51min	11h 15min	10h 21min	7h 27min
SRST - NPR	10h 9min	-	-	12h 24min	8h	9h 21min	12h 57min	-	11h 9min	11h 30min
LST - RST	0	0	0	0	0	3h 27min	0	0	0	0
RST - RCR	57min	36min	2h 12min	1h	2h 57min	0	5h 27min	1h 45min	9min	2h 45min
RST - WNR	1h 24min	1h 27min	3h 33min	1h 39min	3h 42min	24min	5h 45min	4h 27min	2h 57min	4h 18min
RST - NPR	4h 51min	-	-	3h 27min	4h 51min	3h 9min	9h 51min	-	3h 45min	8h 21min
Snow end time - RCR	1h 30min	-	9 min	42min	-	1h 30min	1h 9min	-	-	-
Snow end time - WNR	1h 57min	30min	1h 30min	1h 21min	-	1h 54min	1h 27min	2h 12min	1h 9min	-
Snow end time - NPR	5h 24min	-	-	3h 9min	-	4h 39min	5h 33min	-	1h 57min	-
RCR - WNR	27min	51min	1h 21min	39min	45min	24min	18min	2h 42min	2h 48min	1h 33min
RCR - NPR	3h 54min	-	-	2h 27min	1h 54min	3h 9min	4h 24min	-	3h 36min	5h 36min
WNR - NPR	3h 27min	-	-	1h 48min	1h 9min	2h 45min	4h 6min	-	48min	4h 3min
Maximum U Reduction	29.25	30.60	34.12	31.24	34.64	17.75	32.59	40.20	37.19	44.75
Snow-Affected Ratio	0.64	1.67	0.85	0.65	0.56	0.22	1.20	0.67	0.74	0.57

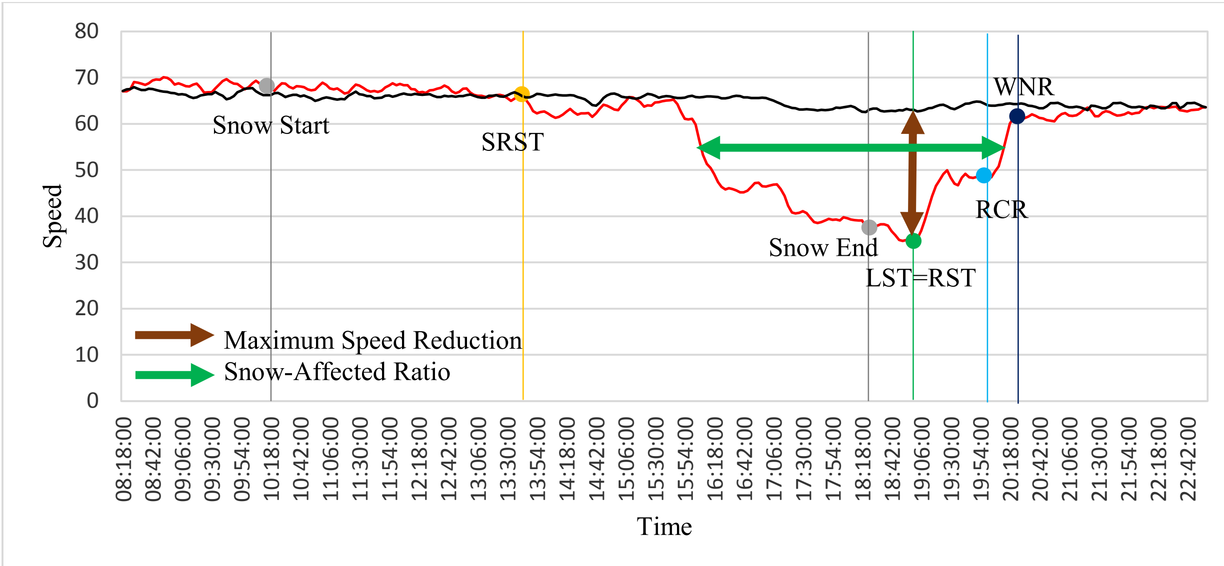

Figure 81: Estimation of Operational Measures for TH.94 EB in Jan. 14. 2012

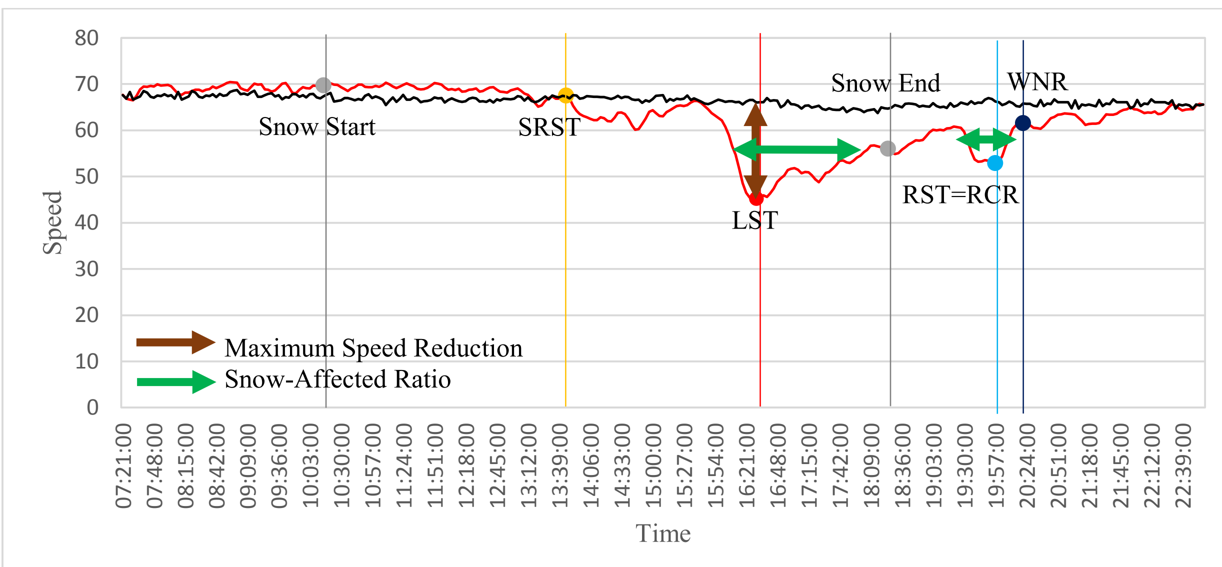

Figure 82: Estimation of Operational Measures for TH.94 WB in Jan. 14. 2012

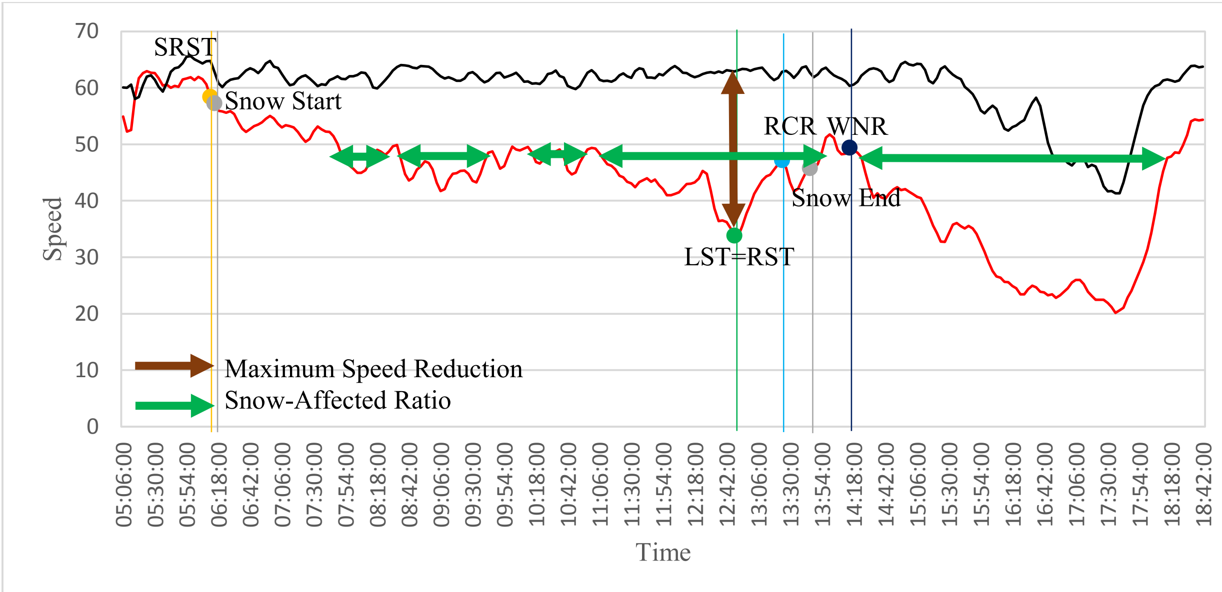

Figure 83: Estimation of Operational Measures for TH.94 EB in Jan. 20. 2012

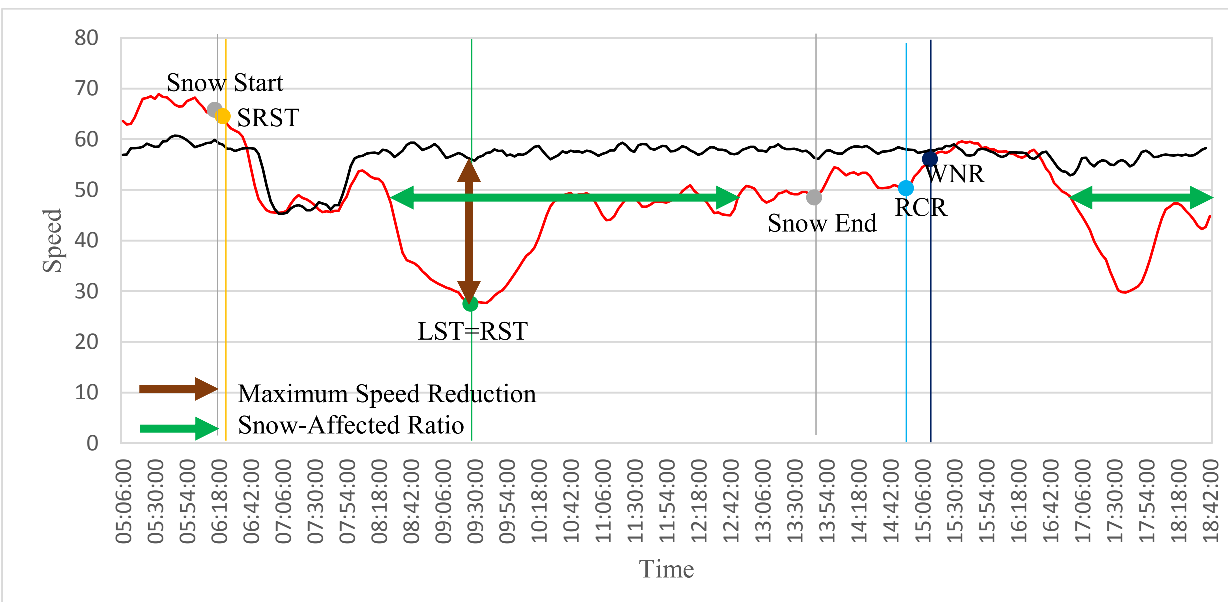

Figure 84: Estimation of Operational Measures for TH.94 WB in Jan. 20. 2012

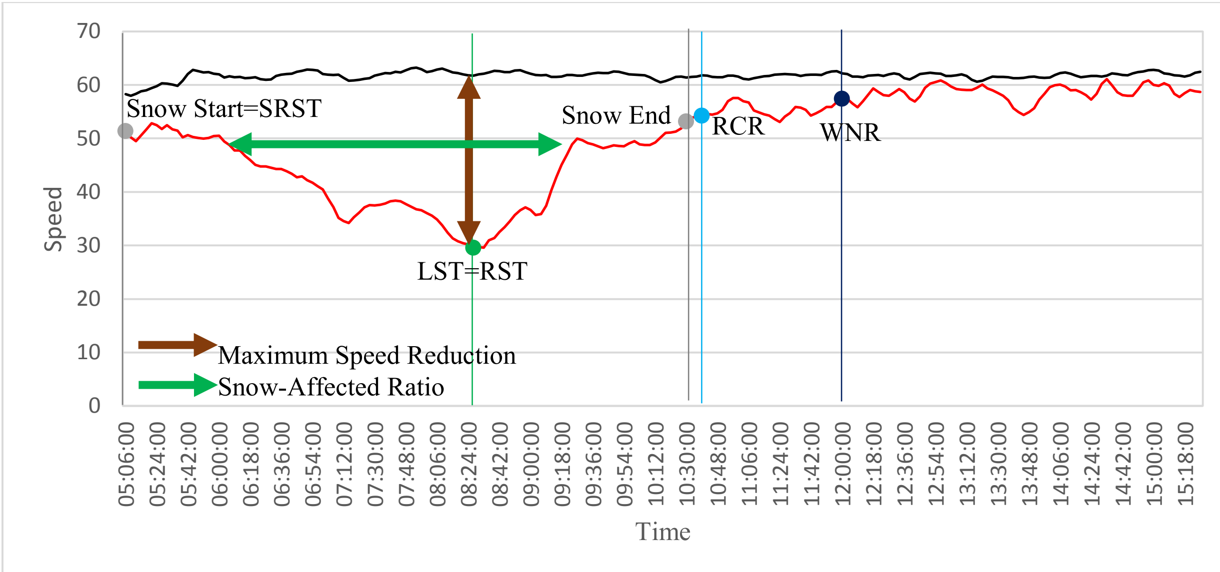

Figure 85: Estimation of Operational Measures for TH.94 EB in Jan. 23. 2012

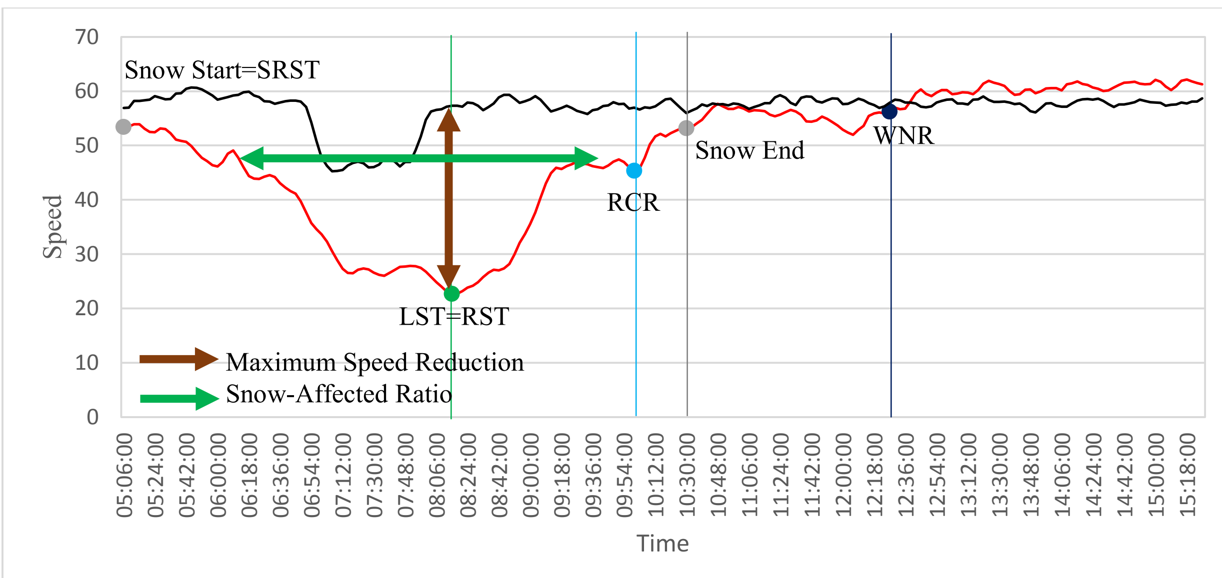

Figure 86: Estimation of Operational Measures for TH.94 WB in Jan. 23. 2012

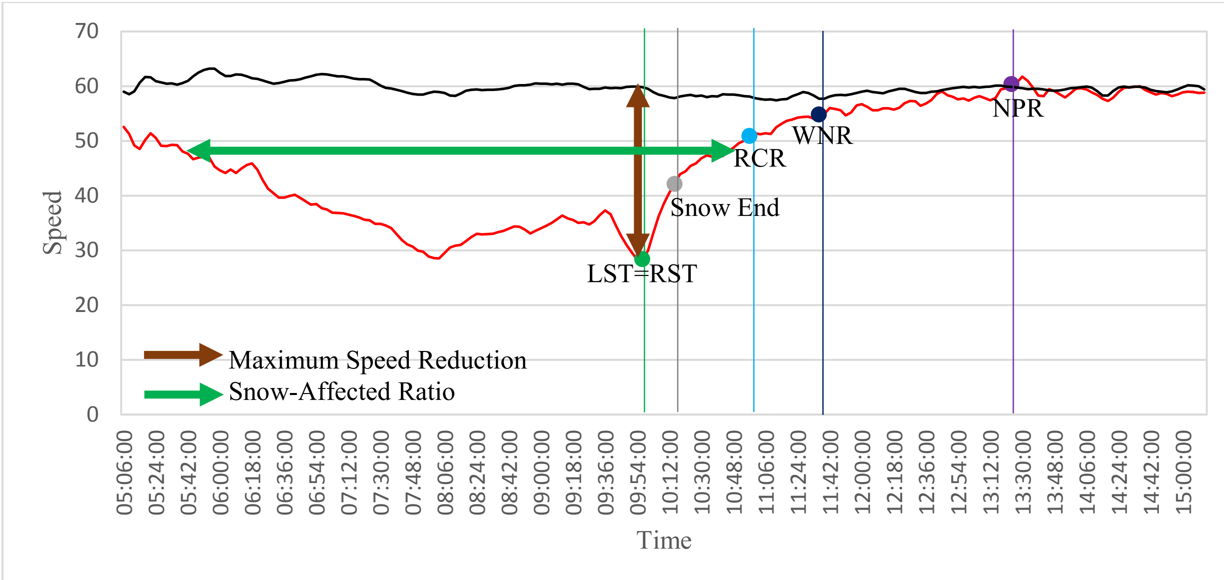

Figure 87: Estimation of Operational Measures for TH.94 EB in Feb. 22. 2013

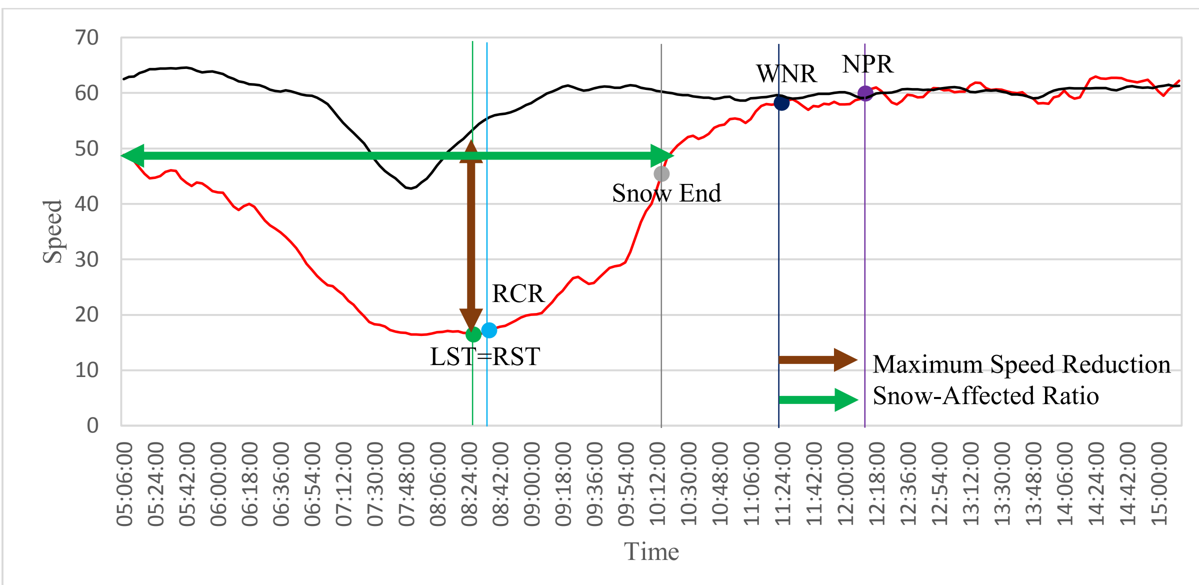

Figure 88: Estimation of Operational Measures for TH.94 WB in Feb. 22. 2013

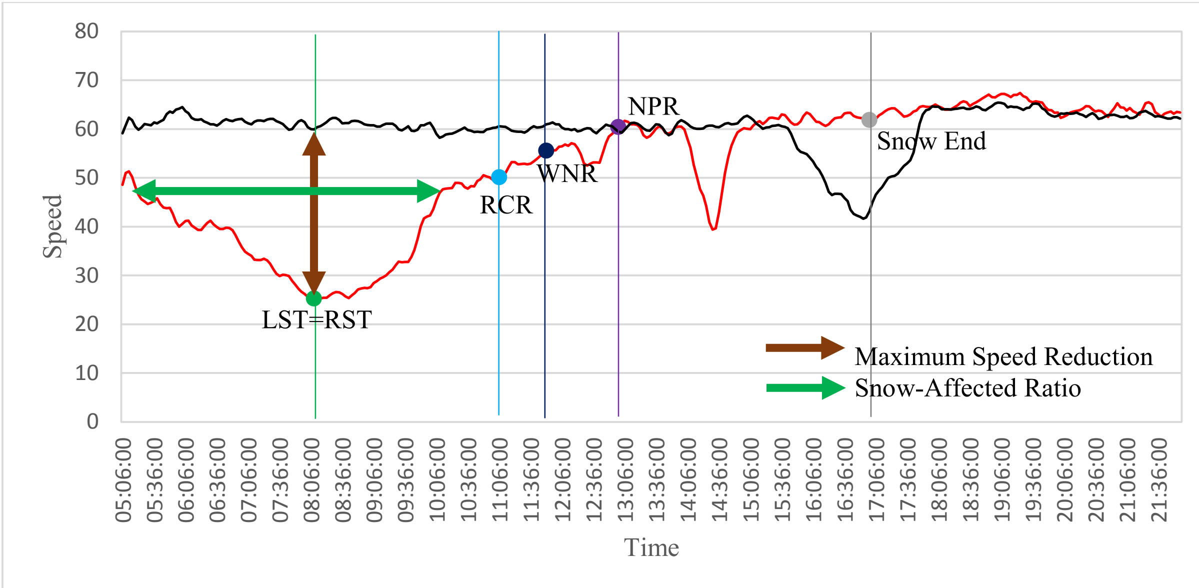

Figure 89: Estimation of Operational Measures for TH.94 EB in Mar. 18. 2013

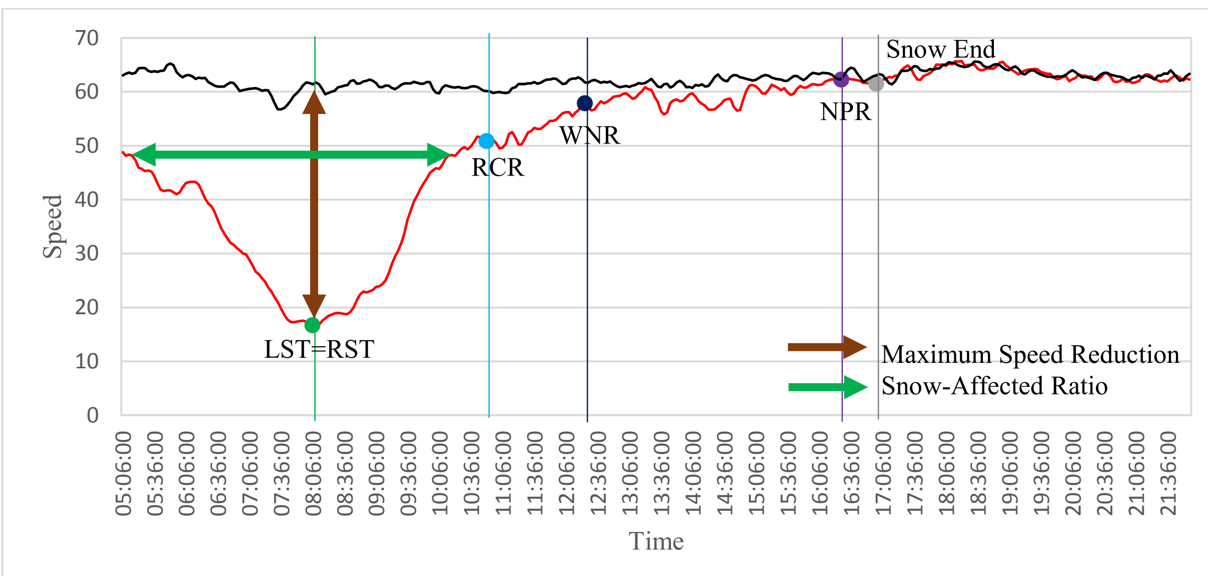

Figure 90: Estimation of Operational Measures for TH.94 WB in Mar. 18. 2013

Table 8 provides the summary of weather conditions collected from the RWIS censors during the snow events. The data types include the snow event duration, road surface temperatures and 24-hour accumulative precipitations for each snow event case. Based on the dataset, it should be noticed that the road weather environment was the worst in Jan. 20. 2012 with its lowest temperature of road surface and the daily precipitation of 2.4 inches in average. The rest of the four snow events show variations in the road surface temperatures from each other, but they consistently show the insignificant level of snow precipitations compared to the one in Jan. 20. 2012.

Table 8: Information on the Selected Snow Events

	1/14/2012	1/20/2012	1/23/2012	2/22/2013	3/18/2013
Snow Event Duration	8h 10min	5h 30min	9h	8h 45min	12h 30min
Average Road Surface Temperature	-11.9°C	-16.3°C	2.4°C	-5.8°C	-2.6°C
Minimum Road Surface Temperature	-13.7°C	-17.7°C	1.5°C	-6.5°C	-4.5°C
Maximum Road Surface Temperature	-8.7°C	-15.5°C	3°C	-5.3°C	-1.5°C
Average of 24hr Accumulative Precipitation	1.2 inch	2.4 inch	0.0 inch	0.3 inch	0.6 inch
Minimum 24hr Accumulative Precipitation	0.8 inch	2.2 inch	0 inch	0 inch	0 inch
Maximum 24hr Accumulative Precipitation	1.6 inch	2.7 inch	0.2 inch	1.8 inch	1.8 inch

In Figure 91, each graph shows relationship between the "Maximum speed reduction" versus the average road surface temperature and the average daily precipitations, respectively. Similarly, Figure 92 contains two graphs which show relationships between the "Ratio of snow-affected time" versus the average road surface temperature and the average daily precipitations. As mentioned above, the effects of the traffic flow level of each snow section was assumed to be controlled for the selected snow events.

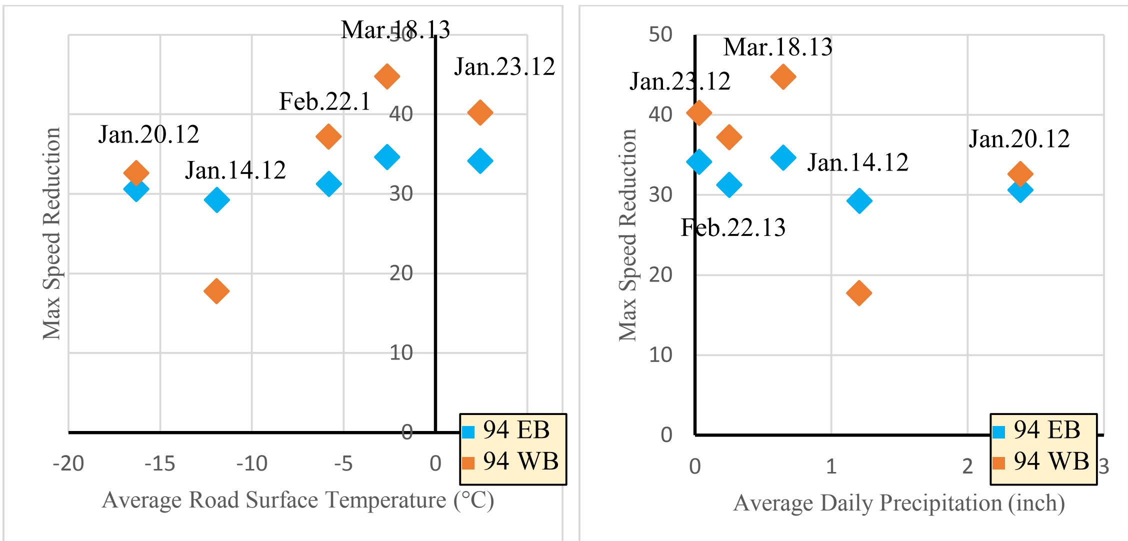

Figure 91: Maximum Speed Reduction vs. Average Road Surface Temperature (Left); Maximum Speed Reduction vs. Average Daily Precipitation (Right)

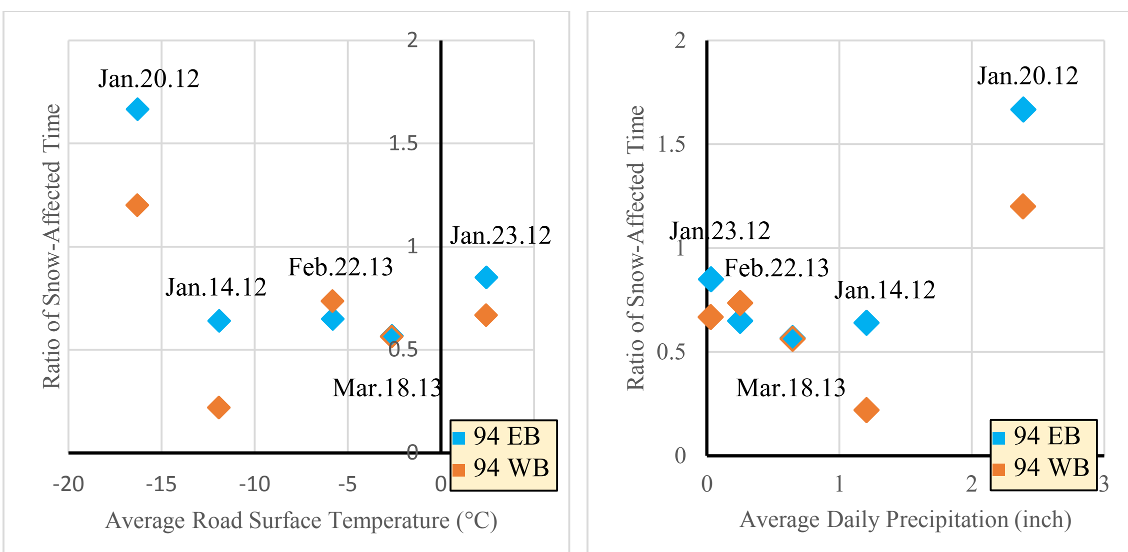

Figure 92: Ratio of Snow-Affected Time vs. Average Road Surface Temperature (Left); Ratio of Snow-Affected Time vs. Average Daily Precipitation (Right)

Following is the summary of observations on the relationship between the operational measure and the road weather conditions, e.g., average road surface temperature and average daily precipitations:

- The operational measures of each directional ways, i.e., TH.94 EB and WB, usually show similar trend to each other during the same snow event.
- The two types of operational measure do not necessarily correspond to each other. For example, the “Maximum speed reductions” of TH.94 EB are mostly lower than those of TH.94 WB, but the “Ratio of Snow-Affected Time” of TH.94 EB are usually higher than those of TH.94 WB.
- The “Maximum speed reduction” does not show any consistent patterns in the relationships with both parameters of road weather conditions.
- The “Ratio of snow-affected time” mostly remains within the range from 0.5 to 1 without regular patterns, and only the operational measure exceeded 1 in Jan. 20. 2012 where the road weather condition was critically inclement compared to other snow event days.

Based on the observations, it can be concluded that the two types of operational measures reflect different aspects of winter snow operations. The “Maximum speed reduction” is a microscopic measure which indicates how effectively the snow operations mitigated the speed reduction at the LST (Lowest Speed Time).

On the contrary, the “Ratio of snow-affected time” is a macroscopic measure which reflects the general impact of snow precipitations on the traffic flow process during snow events. Therefore, the “Ratio of snow-affected time” is reflective against the general features of road weather conditions during snow events, such as the average road surface temperature and/or average snow precipitations. While, it is not necessarily the case for the "Maximum speed reduction," as the maximum speed reduction is determined by the relatively short-period road weather conditions.

CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

7.1. Summary of Findings

This study was motivated by the need to use the alternative operational measures which can accurately and reliably quantify the performance of winter snow management during snow events. The major accomplishment of this study is the automatic process developed for estimating the alternative traffic data-based operational measures. The automatic process was applied to a sample snow section in the Twin Cities, MN, using the traffic data collected during the five selected snow events in 2012-2013.

First, the section-wide traffic flow parameters, i.e., the section-wide speed and the section-wide density, were developed to be used in the analysis on the traffic flow process during snow events. The section-wide traffic flow process during snow events was analyzed with the traffic data collected from the four snow sections in the metro freeways in Twin Cities, MN, during the winters in 2011-2013. The key findings from the analysis of traffic flow process during snow events are as follows:

- The traffic flow process during a snow event consists of 3 periods: 1) Speed reduction period, 2) Road condition recovery period, and 3) Normal pattern recovery period. These 3 periods were commonly observed among the different snow event cases.
- During the "Speed Reduction Period," i.e., from the SRST (Speed Reduction Starting Time) to the RST (Recovery Starting Time), three types of reduction patterns were observed depending on the traffic volume and snow precipitation levels.

- Reduction pattern 1: Both both density and speed levels are decreased. This pattern was mostly observed under the diminishing traffic volumes during off-peak time, regardless of the precipitation intensity.
- Reduction pattern 2: It was observed that the density increased while the speed decreased. This pattern was mostly observed under the light precipitation of snow. It explains the driver's behaviors that they are not hesitant to decrease the gap distance from the preceding vehicle to maintain the original throughput in compensation of the reduced speed.
- Reduction pattern 3: It was observed that the density sustained while the speed decreased. This pattern was mainly observed under the heavy precipitation of snow. It reflects the drivers' cautious behavior where they tend to maintain or increase the gap distance from the preceding vehicles while they decrease their speed.

- During the "Road Condition Recovery Period," i.e., from the RST (Recovery Starting Time) to the RCR (Road Condition Recovery time), 3 different types of the speed-density variation patterns resulting from the snow plowing operations were observed depending on the different traffic volumes within the snow section. The patterns include: Loop-disturbance patterns, Density-disturbance patterns, and Vertical-increasing patterns.
- Based on the CCTV images collected during the snow events, it was observed that the time of the last snow plowing pattern which after the speed achieved the posted speed limit corresponded to the time where the road surface condition became bared.

- During the "Normal Pattern Recovery Period," i.e., from the RCR (Road Condition Recovery Time) to the NPR (Normal Pattern Recovery Time), the two types of recovery patterns were observed depending on the traffic volumes during the recovery periods:
    - Recovery pattern 1: When traffic is uncongested, the speed variations were observed to recover the wet-normal free-flow speed level which was lied within 80-100% of the average dry-normal speed level.
    - Recovery pattern 2: When traffic is congested, the speed-density relationship patterns were observed to recover the fundamental relationships of traffic flow where the speed was decreasing while density was increasing. Yet, the speed level at a certain density is lower than that of the dry-normal days.

Based on the above finding, a set of the phase change points were identified and they reflect the state-changes of the road surface conditions at a given location. The phase change points identified in this study include SRST (Speed Reduction Starting Time), LST (Lowest Speed Time), RST (Recovery Starting Time), RCR (Road Condition Recovery Time), PSR (Posted Speed Recovery Time), WNR (Wet-Normal Pattern Recovery Time), and NPR (Normal Pattern Recovery Time).

In particular, RCR point was defined to be used it as a surrogate for the "bare lane regain time" which is the main operational measure currently used by MnDOT. To identify RCR point, the characteristics of the snow plowing patterns within the traffic flow variations were explored. The snow plowing patterns were identified by the investigation of the CCTV images which were able to capture the snow plowing trucks in operations within the snow section. Among the snow plowing patterns possibly identified in multiple numbers, RCR was selected as the last point of the snow plowing patterns before reaching the posted speed limit to adhere to the standards of “bare lane regain time” defined by MnDOT.

The phase change points identified in the traffic flow variations were used to develop the alternative operational measures for winter snow management. The alternative operational measures include the time difference between the two phase change points of interests, the “Maximum speed reduction at LST”, and the “Ratio of snow-affected time.”

The automatic process to identify the traffic data-based operational measures were developed and incorporated into TICAS (Traffic Information and Condition Analysis System) which was developed at University of Minnesota Duluth.

The automatic process was then applied to the sample snow section, i.e., TH.94 eastbound and westbound, for the selected five snow events in 2012-2013. The results of the example estimation for the sample snow section showed that each of the operational measures were able to reflect and inform the various aspects of the snow operations activities during snow events, such as the time taken to transfer between the different phase points, the maximum speed reduction during snow events, and the time where the speed is less than the accepted level to be considered as normal.

7.2. Limitations

This research has explored the effect of road weather conditions on the traffic flow process while considering the snow plowing activities. The findings were then used to identify the phase-transition points in the snow-affected traffic flow variations to quantify the effectiveness of the snow operations during snow events. In the course of this research, there were some points remained worth investigated to enhance the automatic process for estimating the operational measures. The key limitations for the current version of the algorithm is as follows:

- The automatic process was not able to access the information about the snow plowing operations, such as the exact times, the circulations and the methods of snow plowing activities, in conducting the analysis of traffic flow process. The improved database will allow the in-depth analysis on the traffic flow process under the various operational conditions.
- The automatic process for identifying RST (Recovery Start Time) needs to be improved for the cases with the long recovery periods and multiple speed drops due to the changeable patterns of snow precipitations. For this, the collection of the local-oriented weather data is required to better identify the possible patterns of the traffic flow process at the RST.
- The automatic process was less accurate in estimating the phase change points for the snow events with the light precipitations. This issue derived from the

premise assumed in this study: the traffic flow recovers to the posted speed limit as a consequence of the bare road conditions. For some cases, the speed reductions during snow events were not so significant that the speed remained close to the speed limit of the given snow section, and/or the traffic disturbance patterns were not easily identified because of the insignificant impact from the snow plowing activities.

- The automatic process to identify the phase change points adopted multiple parameters which were experimentally determined based on the patterns observed in the given study cases. In the next term of this research, it is recommended to enhance the algorithm to identify the phase change point only based on the spatial pattern in the speed-density plot.
- The average dry-normal pattern developed to identify SRST and NPR is possibly misled by the traffic patterns with exceptional cases, such as traffic accident, roadwork or special event around the area. It is required to enhance the process to determine the dry-normal days based on the given traffic variations.

7.3. Further Research Needs

Considering the findings and the achievements of this research, some topics could be brought up to recommend for the future research which could follow-up the current needs of the traffic operations areas:

- It can be studied the effect of the different strategies of snow operations, i.e., the time intervals of the plowing activities and the number of plowing trucks for each assignment, on the traffic flow patterns and its recovery process.
- Both mesoscopic and macroscopic approaches can be studied to model the behavior of the traffic flow during the snow events, i.e., for each of the speed reduction and recovery period. The resulting models can be applied to enhance the process for estimating the effectiveness of snow maintenance strategies.
- The relationships between the traffic flow process and other weather events, such as rain and fog can be studied to develop a comprehensive set of traffic flow models that are sensitive to time-variant weather and road surface conditions.

REFERNCES

[1] Federal Highway Administration, "Road Weather Management Program," FHWA, Washington, D. C., 2004.

[2] S. Kim, C. Park and E. Kwon, "Estimation of Speed Recovery Time with Traffic Data for Winter Snow Mangement Operations," *Transportation Research Board 91st Annual Meeting, Washington, D. C.,* 2012.

[3] Iowa Highway Research Board, "Performance Measurement for Highway Winter Maintenance and Operation," IHRB, Ames, Iowa, 2009.

[4] C. Lee, W. Loh, X. Qin and M. Sproul, "Development of New Performance Measure for Winter Maintenance by Using Vehicle Speed Data," *Transportation Research Record 2055, Transportation Research Board of the National Aacademies, Washington, D. C.,* pp. 89-98, 2008.

[5] "Michigan State DOT's Measurement of Regain Time," *Traffic Technology International,* p. 29, October/November 2013.

[6] "Fourteen-year average from 1995 to 2008 analyzed by Noblis," FHWA - Office of Operations, [Online]. Available: http://www.ops.fhwa.dot.gov/.

[7] A. J., B. Mills, M. Leahy and J. Suggett, "Weather as a Chronic Hazard for Road Transportation in Canadian Cities," *Natural Hazard,* vol. 28, no. 2-3, pp. 319-343, 2003.

[8] D. Eisenberg and K. Warner, "Effects of Snowfalls on Motor Vehicles Collisions, Injuries, and Fatalities," *American Journal of Public Health,* vol. 95, no. 1, pp. 120-124, 2005.

[9] A. T. Ibrahim and F. L. Hall, "Effect of Adverse Weather Conditions on Speed-Flow-Occuancy Relationships," *Transportation Research Record, TRB, National Resesarch Council,* vol. 1457, pp. 184-191, 1994.

[10] H. Rakha, M. Farzaneh, M. Arafeh and E. Sterzin, "Inclement Weather Impacts on Freeway Traffic Stream Behavior," *Transportation Research Record: Journal of Transportation Research Board,* vol. 2071, pp. 141-149, 2008.

[11] "Highway Statistics Publications," Federal Highway Administrations (FHWA), 1997-2005.

[12] R. Maccubin, "Analysis of Weather Incident Effect on Commercial Vehicle Mobility in Large U.S. Cities," Mitretek Systems, Falls Church, VA, 2002.

[13] R. Alfelor, R. Billot, N. E. Faouzi and P. Pisano, "Approaches and Gaps in Weather Responsive Traffic Management - US and European Perspectives," *The 92th Annual Meeting of Transportation Research Board 2013,* 2013.

[14] FHWA Road Weather Management Program, "Microscopic Analysis of Traffic Flow in Inclement Weather," US Department of Transportation, December 2010.

[15] "Incorporating Weather Impacts in Traffic Estimation and Prediction Systems," FHWA Road Weather Management Program, US Department of Transportation, 2009.